Journal of Applied Ecology British Ecological Society

# Global analysis of seagrass restoration: the importance of large-scale planting

| | |
|---|---|
| Journal: | *Journal of Applied Ecology* |
| Manuscript ID: | JAPPL-2015-00534.R1 |
| Manuscript Type: | Standard Paper |
| Date Submitted by the Author: | n/a |
| Complete List of Authors: | van Katwijk, Marieke; Radboud University, Environmental Science<br>Thorhaug, Anitra; Yale University,<br>Marba, Nuria; IMEDEA,<br>Orth, Robert; VIMS,<br>Duarte, Carlos; King Abdulaziz University,<br>Kendrick, Gary; University of Western Australia,<br>Althuizen, Inge; Radboud University,<br>Balestri, Elena; Pisa University,<br>Bernard, Guillaume; GIPREB,<br>Cambridge, Marion; University of Western Australia,<br>Cunha, Alexandra; Universidado do Algarve,<br>Durance, Cynthia; Precision Identification,<br>Giesen, Wim; Mott MacDonald,<br>Han, Qiuying; Chinese Academy of Sciences,<br>Hosokawa, Shinya; Port and Airport Research Institute,<br>Kiswara, Wawan; LIPI,<br>Komatsu, Teruhisa; University of Tokyo,<br>Lardicci, Claudio; Pisa University,<br>Lee, Kun-Seop; Pusan National University,<br>Seven, more coauthors; Several Institutes, |
| Key-words: | coastal ecosystems, ecosystem recovery, global restoration trajectories, positive feedback, seagrass rehabilitation, seagrass mitigation, allee effect |
| | |

# Global analysis of seagrass restoration: the importance of large-scale planting.

Subtitle: Large-scale required for seagrass restoration

Marieke M. van Katwijk[1], Anitra Thorhaug[2], Núria Marbà[3], Robert J. Orth[4], Carlos M. Duarte[3,5,6], Gary A. Kendrick[5], Inge H.J. Althuizen[1], Elena Balestri[7], Guillaume Bernard[8], Marion L. Cambridge[5], Alexandra Cunha[9], Cynthia Durance[10], Wim Giesen[1,11], Qiuying Han[12], Shinya Hosokawa[13], Wawan Kiswara[14], Teruhisa Komatsu[15], Claudio Lardicci[7], Kun-Seop Lee[16], Alexandre Meinesz[17], Masahiro Nakaoka[18], Kate R. O'Brien[19], Erik I. Paling[20] Chris Pickerell[21], Aryan M.A. Ransijn[1], Jennifer J. Verduin[22]

[1] Department of Environmental Science, Institute for Water and Wetland Research, Radboud University Nijmegen, Faculty of Science, Heyendaalseweg 135, 6525 AJ Nijmegen, Netherlands.

[2] Institute for Sustainable Forestry, School of Forestry and Environmental Studies, Yale University, Greeley Laboratories, Prospect St, New Haven, CT 06511, USA

[3] Department of Global Change Research. IMEDEA (CSIC-UIB) Institut Mediterrani d'Estudis Avançats, C/ Miguel Marqués 21, 07190 Esporles, Spain

[4] Virginia Institute of Marine Science, 1208 Greate Road, College of William and Mary, Gloucester Point, Virginia 23062, USA

[5] The UWA Oceans Institute and School of Plant Biology, University of Western Australia, 35 Stirling Highway, Crawley 6009, Australia

[6] Faculty of Marine Sciences, King Abdulaziz University, P. O. Box 80207, Jeddah, 21589, Saudi Arabia

[7] Dipartimento di Biologia, Pisa University, Via Derna 1, 56126, Pisa, Italy

[8] GIPREB (Gestion Intégrée pour la Prospective et la Réhabilitation de l'Etang de Berre) Cours Mirabeau, Berre-l'Étang, France

[9] Centro de Ciências do Mar (CCMAR), Edificio 7, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

[10] Precision Identification, 3622 West 3rd Avenue Vancouver, B.C. V6R 1L9, Canada

[11] Euroconsult Mott MacDonald, P.O. Box 441, 6800 AK Arnhem, The Netherlands

[12] Key Laboratory of Coastal Zone Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research (YIC), Chinese Academy of Sciences (CAS), Shandong Provincial Key Laboratory of Coastal Zone Environmental Processes, YICCAS, Yantai Shandong 264003, P.R. China

[13] Coastal and Estuarine Environmental Research Group, Port and Airport Research Institute, Nagase, Yokosuka, Kanagawa 239-0826 , Japan

[14] Research Centre for Oceanography, Indonesian Institute of Sciences, Jl. Pasir Putih No. 1, Ancol Timur Jakarta Utara, 14430 Indonesia

[15] Atmosphere and Ocean Research Institute, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8564, Japan

[16] Department of Biological Sciences, Pusan National University, Pusan 609-735, Republic of Korea

[17] University Nice Sophia Antipolis, EA ECOMERS 4228, F-06108 Nice 2, France

[18] Akkeshi Marine Station, Field Science Center for Northern Biosphere, Hokkaido University, Akkeshi Hokkaido 088-1113, Japan

[19]School of Chemical Engineering, The University of Queensland, St Lucia, 4072, Australia

[20] Ichthys Onshore LNG, 11/14 Winnellie Road, Winnellie NT 0820, Australia

[21] Cornell Cooperative Extension of Suffolk County, Marine Program, 423 Griffing Avenue, Suite 100, Riverhead, New York 11901, USA

[22] Murdoch University, School of Environmental Science, South Street Murdoch, 6150 Perth, Australia

Corresponding author: Marieke M. van Katwijk, Department of Environmental Science, Institute for Water and Wetland Research, Radboud University Nijmegen, Faculty of Science, Heyendaalseweg 135, 6525 AJ Nijmegen, Netherlands. Tel. +31243652478, e-mail m.vankatwijk@science.ru.nl

## Summary

- In coastal and estuarine systems, foundation species like seagrasses, mangroves, saltmarshes, or corals provide important ecosystem services. Seagrasses are globally declining and their reintroduction has been shown to restore seagrass functions. However, seagrass restoration is often challenging, given the dynamic and stressful environment that seagrasses often grow in.
- From our worldwide meta-analysis of seagrass restoration successes (1786 trials), we describe general features and best practice for seagrass restoration. We confirm that removal of threats is important prior to replanting. Reduced water quality (mainly eutrophication), and construction activities led to poorer restoration success than for instance dredging, local direct impact and natural causes. Proximity to and recovery of donor beds were positively correlated to trial performance. Planting techniques can influence restoration success.
- The meta-analysis shows that both trial survival and seagrass population growth rate in survived trials are positively affected by the number of plants or seeds initially transplanted. This relationship between restoration scale and restoration success was not related to trial characteristics of the initial restoration. The majority of the seagrass restoration trials has been very small, which may explain the low overall trial survival rate (i.e., estimated 37%).
- Successful regrowth of the foundation seagrass species appears to require crossing a minimum threshold of reintroduced individuals. Our study provides the first global field evidence for the requirement of a critical mass for recovery, which may also hold for other foundation species showing strong positive feedback to a dynamic environment.

- ***Synthesis and Applications***: For effective restoration of seagrass foundation species in its typically dynamic, stressful environment, introduction of large numbers is seen to be beneficial and likely serves two purposes. First, a large-scale planting increases trial survival - large numbers ensure the spread of risks which is needed to overcome high natural variability. Second, a large-scale trial increases population growth rate - by enhancing self-sustaining feedback which is generally found in foundation species in stressful environments such as seagrass beds. Thus, by careful site selection and applying appropriate techniques, the spreading of risks and enhancing self-sustaining feedback in concert increase success of seagrass restoration.



## Introduction

Coastal and estuarine habitats are characterised by dynamic and stressful environments. Many coastal ecosystems are dominated by one or few 'foundation' species (*cf.* Bruno and Bertness, 2001, species that positively affect the fitness of other species through their modification of the environment). Seagrass beds are a clear example of ecosystems dominated by foundation species. They typically ameliorate stress, usually passively by the mere presence of their structure creating shelter and sediment stabilisation, resulting in lower water turbidity and amelioration of wave action, but also by processes influencing water quality like nutrient uptake. This ecosystem engineering by seagrass beds (cf Jones et al. 1994) forms the basis of key ecosystem services, including erosion control (Hansen and Reidenbach 2012, Christianen et al. 2013), carbon sequestration for climate change mitigation (Thorhaug et al. 2009, McLeod et al. 2011, Duarte et al. 2013a, Duarte et al.

2013b), fisheries habitat support (Watson et al. 1993, McArthur and Boland 2006, Unsworth et al. 2010), and high biodiversity, including iconic and highly endangered species (Hemminga and Duarte 2000).

Seagrasses rank among the most productive yet highly threatened ecosystems on earth with rates of decline accelerating globally from a median of 0.9 % $yr^{-1}$ before 1940 to 7 % $yr^{-1}$ since 1990 (Waycott et al. 2009). Legislation for protection and restoration of seagrass habitat as well as for improving coastal quality has been established in many nations to prevent further losses and facilitate recovery (Duarte 2002, Orth et al. 2006). Water quality improvements have led to seagrass recovery in a limited number of studies (Greening and Janicki et al. 2006, Cardoso et al. 2010, Vaudrey et al. 2010, but see Valdemarsen et al. 2011), but has apparently not slowed the global rate of loss of seagrass substantially. Seagrass restoration is thus a necessary additional instrument to offset the loss of seagrass habitat's ecosystems biodiversity and their services. Restoration efforts have been performed worldwide to compensate or mitigate seagrass losses and have been shown to enhance the associated ecosystem services (Paling et al. 2009). However, seagrass restoration seems to have low performance rates (Fonseca et al. 1998), though a comparative quantitative global overview on the performance of seagrass restoration is lacking and the processes influencing success or failure of restoration programs have not been systematically assessed.

In this paper we use a global, systematic analysis of seagrass restoration to identify characteristics that promote seagrass restoration success and present best practices to support and develop existing restoration guidelines. Second, we study the effect of restoration scale (i.e., initial number of reintroduced plants) on the trial survival and population growth rate in survived trials. A larger restoration scale is hypothesised to be beneficial for two reasons: to overcome the stochasticity related to the dynamic environment (e.g., Morris & Doak 2002), and to provide a critical mass for stress amelioration by the starting founders (i.e., the initial planting unit) themselves (cf, Bos & van Katwijk, 2007, van der Heide et al. 2007, 2011, Carr et al. 2010, 2012, Orth et al. 2012). We recorded trial survival and population growth of survived trials in 1786 seagrass restoration trials described in 215 studies. To analyse best practice and to test for confounding effects with restoration scale, we analysed the trial characteristics regarding environmental variables, techniques and species used.

We find both trial survival and population growth rate in survived trials positively affected by the numbers of plants or seeds initially planted. This relation was not confounded by other trial characteristics such as species, method of planting, or environmental characteristics at the recipient sites. As the majority of the seagrass restoration trials has been very small ( 55% had fewer than 1000 specimens initially planted), this likely explains the low trial survival rates recorded. From this we have derived a conceptual framework to demonstrate how spreading of risks and enhancing self-sustaining feedback in concert increases restoration success.

## Materials and methods

We compiled data from restoration trials conducted worldwide from published articles listed in Web of Science (92 papers), grey literature (120 reports) and own unpublished data (187 trials), from 17 countries, resulting in 1786 trials. Each of the 1786 rows in the dataset represents a trial, the oldest one planted in 1935. A trial consists of one or more shoots or seeds that have the same 'treatment', i.e., they are planted at the same location, with similar techniques and treatments in the same year and season, using the same species and plant material. Occasionally, trials from multiple years could not be separated and we recorded the first year or the year of largest effort as the planting year. (Sources used: see Appendix S1 in Supporting Information). The study is not a traditional meta-analysis (e.g. Harrison 2011); firstly, we aimed to not exclude any reported trial (resulting in many missing values); secondly, the recorded characteristics usually have no controls, so effect sizes can only be estimated relatively between categories (e.g. plant material has the categories: seeds, sods, rhizome fragments or seedlings); thirdly, the data did not allow for assignment of a nesting factor like sources or planting teams. This is because very similar trials regarding site and techniques are sometimes based on multiple sources and planting teams, and vice versa, very diverse trials are sometimes listed by single sources or planting teams..

Effect of restoration scale on trial survival and population growth rate

To test for restoration scale effect (i.e., initial number of reintroduced plants) on trial survival we recorded trial survival (1=one or more shoots survived or 0=none of the shoots survived) at the end of the monitoring period and performed survival analyses (see below). The seagrass population growth rate in survived trials was calculated as the intrinsic rate of increase of an exponential growth function, log (nsht/nsh0) / t, where nsh0 is the number of shoots[1] at t=zero and nsht is the number of shoots at the end of monitoring after t months. In total, 1060 trials contained data to perform the survival analysis and 486 trials contained data to calculate seagrass population growth rate in survived trials.

The relationship between trial survival and initial number of shoots/seeds (restoration scale) was tested in five categories, 1: <100 shoots/seeds, 2: 100-1000 shoots/seeds, 3: 1000-10,000 shoots/seeds, 4: 10,000-100,000 shoots/seeds, 5: > 100,000 shoots/seeds, using survival analysis (SAS PROC LIFETEST testing whether the scale categories have identical survivor functions using a proportional hazard model). Trial survival after 2 years was estimated using Kaplan-Meier estimation of the survival function using the same SAS procedure. The relationship between population growth rate (increase in number of shoots or seeds month$^{-1}$) and the five categories of initial number of shoots/seeds scale was analysed and tested using ANOVA.



Estimation of long term trial survival

To estimate long term trial survival, we went through the following steps. Because monitoring periods and frequency differed between trials, and many trials were monitored only once, we first analysed trial survival (1=one or more shoots survived or 0=none of the shoots survived at the moment of monitoring) *per phase*. We distinguished three phases: (1) first 9 months; (2) between 10 and 22 months (thus including minimally one adverse season; and (3) more than 22 months (thus including 2 adverse seasons). In general, adverse seasons can either be autumn/winter (e.g., storms, colds) or summer (e.g., high temperature, high salinity, desiccation). Second, trial survival (1 or 0) was averaged for each of the 3 phases and

[1] Shoots refer also to seeds or seedlings that were used in few trials

the three averages were multiplied to obtain a conservative estimate of overall trial survival at the long term (i.e., representing a median monitoring duration of 36 months, see Table 1). 1656 out of 1786 trials had one or more data on trial survival (one or more monitoring events).

Factors affecting restoration performance

To evaluate best practice and to test for confounding effects, 15 trial characteristics were analyzed simultaneously with restoration performance. Restoration performance was expressed by a semi-quantitative measure “integrated success score” which allowed us to evaluate 1289 trials rather than the 478 trials that had quantitative data (which was not sufficient for the evaluation of trial characteristics having many missing values). Integrated success score (ISS) was composed of two metrics: (1) initial trial survival being 1 (or 0) when plants were still present (or had disappeared) in the trial at a monitoring event in phase 1 (≤ 9 months); and (2) long-term planting performance during phase 3 which was quantified by assigning scores to the trials that had data monitored in phase 3 (> 22 months, 414 trials), with scores: 0=lost during phase 3, 1=declined, 2=equal presence and 3=increased since planting. These scores were based upon very diverse monitoring and evaluation methods (i.e., number of shoots, areal development, percentage survival, or textual evaluation, or a combination of those). During the intermediate phase (9-22 months) trials were rarely monitored, therefore these data were only used for the estimation of overall survival of all trials, see above, but not for the evaluation of trial performance. ISS was calculated by multiplying the *mean* initial trial survival by the *mean* long-term trial performance. Both means were calculated per category of the trial characteristics (calculation per trial was not possible because only few trials had data for both metrics). The standard deviation of the mean of the integrated success score was computed from the standard deviations of the initial trial survival and the long-term trial performance after initial survival.

Trial characteristics tested were: seagrass species, reason for planting (categories: restore natural values, mitigation for damage, research and test plots), cause of decline (no decline, substrate-related, construction, local direct impact, natural causes and water quality, see Table 2), removal of threats (no threats, complete removal, partial removal), distance from donor site (<1 km, 1-10 km, 10-50 km, >50 km), donor site recovered (yes/no), bioturbation (yes/no), depth (0 – 0.5 m, 0.5-1 m, 1-2m, 2-4 m, >4 m), emergence (subtidal/intertidal), anchoring technique (weights, staples, none and non-weighted frames, see table 3), type of plant material (sods, rhizome fragments, seeds, seedlings, see table 3), fertilisation (yes/no), planting methods (manual/mechanical), habitat manipulation (none, anti-bioturbation measures, sediment stabilisation), protection measures (none, against hydrodynamics, against grazing). The magnitude of response (effect size) describes the difference between integrated success scores (ISS, calculation see above) of the categories with the highest and the lowest value for ISS (i.e., $ISS_{highest} / ISS_{lowest}$); most characteristics do not have a control category, so these differences are relative to each other.

A logistic regression and one-way ANOVA were used to test the effect of 15 trial characteristics on two measures for trial performance, namely initial trial survival (≤ 9 months) and long-term trial success (> 22 months), respectively. All analyses were univariate because the 15 trial characteristics had many missing values (e.g. no studies had information on all 15 characteristics). To identify characteristics that had significantly different performance metrics between their categories, we performed contrast tests (with statistics based on the asymptotic chi-square distribution of the Wald statistic) and Tukey's post-hoc tests, respectively. Similarly, to test for possible confounding effects between the initial number of shoots/seeds (=restoration scale) and other trial characteristics, we first used ANOVA to identify characteristics that were significantly affected by the number of shoots/seeds initially planted. To identify whether these characteristics could have confounded effects, we estimated whether the initial number of shoots/seeds correlated positively with total trial performance. A positive correlation between the initial numbers of shoots/seeds and restoration performance indicates the existence of confounding effects.

All statistical analyses were performed in SAS 9.2 (http://support.sas.com, consulted on 25 June 2014 and 15 June 2015).



## Results

### Analysis of seagrass restoration trials

Seagrass restoration trials started during the first half of the twentieth century, but efforts remained low until the 1970's, with 20-60 trials initiated per decade. In the 1970's, when seagrass loss started to accelerate (Waycott et al. 2009), the interest in restoring seagrass meadows rapidly increased. Since then, about 450 new trials were initiated globally per decade (Figure S1a). Most (68 %) documented trials were conducted along the temperate and subtropical coastlines of the northern hemisphere (Figure 1). Most restoration areas were previously colonised by seagrass meadows lost due to water quality deterioration (54 %, chiefly eutrophication), coastal construction (15 %) and mechanical destruction of the habitat (8 %), as was reported in the documented trials. The objectives of seagrass restoration were to restore natural values (31 %), mitigate damage and loss (15 %) and gain knowledge (54 %).

One third of the seagrass flora, 26 species, spanning the entire range of size and growth rates among the seagrass flora, was utilised in restoration programs. However, a single species, the temperate *Zostera marina* with the broadest geographical distribution, was utilized in 50% of the reviewed trials. For all seagrass species, rhizome fragments with shoots (55 %) and sods and plugs (24 %) were the most common material planted, whereas seedlings, seeds and seed-bearing shoots have been used in but a few seagrass – most frequently *Z. marina* - restoration programs (12 %, 8 % and 1 %, respectively).

Seagrass restoration trials were on the average small scale with fewer than 409 shoots/seeds and a 0.93 $m^2$ standardised plant area (i.e., the area that these shoots/seeds would occupy in a full cover or coalesced situation, calculated per species), although occupied areas extended to 3 to 4 orders of magnitude larger with far greater number of shoots/seeds for the larger trials (figure 1, table 1). Monitoring was on the average 12 months or less (50 %). However, monitoring duration extended beyond 2 years for 27.5 % of the restoration trials and the longest monitoring period was 38 years (*Thalassia testudinum* in Florida, planted in 1973 (Thorhaug 1974 and unpublished data) (table 1)).

**Analysis of best practice of seagrass restoration**

Traditional seagrass restoration guidelines recommend careful site selection, i.e. a sheltered location with an adequate light environment, and recommend reversal of habitat degradation prior to restoration. Data on shelter and light availability were very scarce and were not included in the analysis. Analysis of the planting depth range showed a weak optimum of intermediate depths. Shallow depth (< 0.50 m) had poorest restoration success, with intertidal sites performing worst (magnitude of response 2.5, Table S1).

The review shows the importance of removal of threats (Table S1). Worldwide, causes of decline are generally known in restoration trials (78% of the cases). However subsequent restoration success varies with different causes: particularly restoration following losses derived from reduced water quality (usually eutrophication) are less successful than, for example, those derived from construction activities (68%), substrate manipulations like dredging and filling (43%), or in areas where there has been no seagrass decline (36%). Recovery and proximity of donor beds were positively correlated to trial performance, with magnitudes of response of 6.4 and 3.9 respectively (Figure 2). Bioturbation can lead to severely reduced initial trial survival and long-term population expansion of survived trials (Table S1). The review shows no consistent correlation between restoration performance and planting season (results not shown).

Seedlings consistently perform worse than any other plant material used, whereas seeds have intermediate scores; anchoring of rhizome fragments using weights gives better success scores than any other combination of plant material and anchoring technique (Figure 2). The magnitude of response to anchoring technique and plant material was 7.1. Any anchoring (weights, staples, frames or using sods) improved the *initial* survival of plants by 84 % on average ($p < 0.0001$, Table S2). The application of weights (sand bags, stones, shells) improved later success scores by 45 % whereas other anchoring methods do not contribute to the later success scores (Table S2). Mechanical planting methods improved initial survival, but somewhat reduced later success scores as compared to manual planting methods (Table S2). Habitat manipulations and protection measures had no positive effect on success (Table S2). Fertilization, if applied (only in 9 cases with long-term data) improved success scores with a magnitude of response of 2.4. Note that for some species fertilization has been demonstrated to inhibit survival and growth (e.g., *Posidonia australis*, Cambridge & Kendrick 2009), illustrating that our meta-analysis provides general trends and averages regarding planting procedures which may not hold for all species or sites.

**The effect of trial scale on restoration success**

Trial survival (proportional hazard model $P < 0.01$) and seagrass population growth rate in survived trials (in number of shoots or standardised area, month$^{-1}$) were directly related to the initial number of shoots or seeds planted. After 23 months, estimated survival of small trials was 22 % (<100 shoots/seeds planted), but trial survival increased to 42 % for the largest scale trials (>100,000 shoots/seeds planted, figure 3a). Likewise, the population growth rate (as increase in number of shoots) in seagrass restoration trials initiated at less than 1000 shoots/seeds was negative, whereas population growth rates for trials with more than 10,000 planted shoots/seeds were positive (figure 3b). The positive effect of restoration scale on both trial survival and population growth rate in survived trials suggests the existence of a threshold of scale of the trial required for restoration progress between 1000 - 10,000 shoots/seeds.

The 'better performing' sites, species and techniques were generally near zero or (weakly) negatively correlated to initial planting scale (Table S3). This robustly shows the absence of confounding effects in the relationship between restoration scale and restoration success.

## Discussion

### Best practice of seagrass restoration

Experiences of seagrass restoration efforts worldwide have been collated in the form of transplantation guidelines (e.g., Addy 1947; Phillips 1980; Thorhaug 1981; Fonseca et al. 1998; Campbell 2002; Short et al. 2002; van Katwijk et al. 2009; Cunha et al 2012), largely based on regional studies and a few species. They recommend careful site and species selection, i.e. a sheltered location with an adequate light environment, and recommend reversal of habitat degradation prior to restoration. They provide best practices addressing anchoring techniques, habitat manipulations, type of plant material used, planting mechanisms, and strategies to cope with the large stochasticity related to the dynamic seagrass environment. However, the drivers of success in seagrass restoration programs have not been objectively and systematically assessed globally, which has been a key factor in preventing improvements based on past experiences (e.g., our analysis shows the absence of a learning curve, Figure S1b). Still, it should be reminded that a global analysis like ours can only provide generalities, and local and regional expertise remains vital for seagrass restoration success.

The importance of shelter and sufficient light is tentatively confirmed in our semi-quantitative worldwide analysis by the slightly better performance of plantings at intermediate planting depths (i.e., very shallow sites probably suffer from wave dynamics, whereas very deep sites are light-limited). Direct evidence cannot be obtained as information on local energy regimes and light availability is largely lacking in literature. Our review confirms the importance of removal of threats. Restoration following losses derived from reduced water quality (usually eutrophication) are less successful than, for example those derived from construction activities, substrate manipulations like dredging and filling, or in areas where there has been no seagrass decline.

Recovery and proximity of donor beds were positively correlated to trial performance. Donor bed proximity indicates nearby seagrass presence, which, together with its recovery potential demonstrates that the environment is suitable for seagrass growth (e.g. Orth et al. 2006). The positive role of donor proximity may additionally be due to 'type-matching' or genetic provenance; the use of local plants could be beneficial due to the presence of locally adapted gene complexes in adjacent meadows (Hämmerli and Reusch 2002; Fonseca 2011; Sinclair et al. 2013). Third, it may also be correlated with the donor material being in better physiological condition when planted given the minimum time between collection and planting.

Regarding planting procedures, the most important factors affecting the success of revegetation trials were anchoring technique and plant material (combined magnitude of response 7.1). During the first months after planting, any anchoring of rhizome fragments or seedlings enhanced survival in comparison to no anchoring. Subsequently, the application of weights (sand bags, stones, shells) significantly improved later success scores in comparison to frames, staples or sods. Weights may mitigate significant water dynamics whereas light frames or staples may become set into motion by water dynamics and thus destabilise the rooting process of the plantings in the long-term. Seedlings consistently perform worse than rhizome fragments, sods or seeds. Mechanical planting methods achieved a somewhat lower success than manual planting methods though initial survival is higher; potentially this reflects the exploratory nature of many of these mechanical planting methods (e.g. Paling et al., 2001).

**Large restoration trials have generally performed better**

The performance of seagrass restoration was largely dependent on the trial scale, since trial survival and population growth rate in restoration trials were directly related to the initial number of shoots or seeds planted. For example, after 23 months, estimated survival of small trials was 22 % (<100 shoots/seeds planted), but trial survival increased to 42 % for the largest scale trials (>100,000 shoots/seeds planted). Likewise, the population growth rate (as increase in number of shoots) in the seagrass restoration trials initiated at less than 1000 shoots/seeds was negative, whereas population growth rates for trials with more than 10,000 planted shoots/seeds were positive, and thus appear to effectively restore the seagrass meadow. The positive effect of restoration scale on both trial survival and population growth rate of survived trials suggests the existence of a threshold of scale of the trial required for restoration progress between 1000 - 10,000 shoots/seeds. Note that the threshold for success will vary over time and in space, depending on factors such as stress levels and natural variability. 55% of the seagrass restoration trials worldwide had less than 1000 shoots or seeds initially planted, which may have contributed to the low overall trial survival from 1786 trials (conservatively estimated to be 37% after median 36 months).

It is critical to point out that seagrass restoration performance is not only related to the trial scale, but also to site characteristics and planting procedures, and may differ between species (as shown in our meta-analysis). This could potentially lead to confounding effects; the larger scale trials may target more suitable sites and techniques than smaller scale trials. However, the 'better performing' sites, species and techniques were generally (weakly) *negatively* correlated to initial planting scale. This robustly indicates the absence of such confounding effects in the positive relationship between restoration scale and restoration success.

**Large restoration scales may generally benefit restoration successes**

Plantings (or new colonisations) are vulnerable to extinction by a multitude of factors, including (i) the variability in external factors of influence (environmental variability), and (ii) positive density dependence or positive feedback (e.g., Morris & Doak 2002). A large-scale planting (particularly when covering a large areal extent) increases the range of environmental conditions experienced by the plants, and hence the likelihood of encountering suitable conditions for positive growth. The local environment is likely heterogeneous due to for example local accumulation of organic matter or macroalgae, bioturbation or mere stochastic variation in water dynamics rising from the hydrodynamic regime. When strong positive feedback occurs, a critical threshold population density is needed to initiate self-facilitating processes (e.g., Morris & Doak 2002, van der Heide et al. 2007, Nystrom et al. 2012). Our meta-analysis of global seagrass restoration supports that both processes occur in seagrass beds. With increasing numbers of initially planted individuals (i) the survival percentage increased, which relates to spreading of risks to overcome environmental variability, and (ii) the population growth rate increased, which relates to positive feedback. Given the typically dynamic and stressful coastal environment of seagrass habitats, and the large number of already identified positive feedbacks in seagrass beds (e.g. Bos and van Katwijk 2007, van der Heide et al. 2007, 2011, Carr et al. 2010, 2012, Orth et al. 2012), this finding may not be surprising. However, our study is the first to show this occurs in seagrass restoration trials at a global scale. To our knowledge, this is the first time this principal has been globally demonstrated as an example of foundation species restoration trends in coastal environments.

Our finding implies that – after careful site and species selection - large-scale plantings are highly preferable in the typically dynamic and/or stressful environments of (former) seagrass beds. To not risk planting under the suggested threshold, it is even advisable to use a larger planting scale than estimated by the planters. However, we recognize this is costly both with respect to extracting donor material as well as operational costs (though regained ecosystem services may compensate and eventually surpass these investment costs, e.g. Duarte et al. 2013b).

If managers decide on a larger number of individuals in a restoration project, these large numbers can be used to increase the density (to reach the threshold for density-dependent feedback, i.e., planting density > density required to restore self-sustaining feedback), but also to increase the spatial extent (in order to spread risks, i.e., the spatial extent of the planting > extent of environmental variability – note that environmental variability relates to spatial heterogeneity resulting from both natural variability and stochasticity). We have depicted the synergy to employ both, in a conceptual framework (figure 4). For a given number of plants available for restoration, focus could be more on either increasing spatial extent or increasing planting density. Clearly, in highly dynamic systems with large unpredictable disturbances, environmental forcing will overrule benefits from restoring feedback, and spreading of risks is of paramount importance (for seagrass beds indicated by e.g., Suykerbuyk et al. submitted this journal). In those cases a focus on large spatial extent is preferable. Reversely, in less dynamic environments, positive feedback may accelerate restoration processes (for seagrass beds indicated by e.g., McGlathery et al. 2012, for shellfish beds e.g. indicated by Schulte et al. 2009), and local high planting densities could be aimed at. This choice should depend upon the wisdom of the local seagrass experts. Our framework implies an 'irony of the test plot': the test plot has the lowest chances for trial survival and subsequent population expansion of all. A surviving and expanding test plot could indicate a bonanza or an exceptionally benign environment, but it can also indicate mere luck. (Note that seagrass restoration practitioners use relatively large numbers of shoots in what are still called 'test plots', so we did not show this effect for 'test plots' in our meta-analysis). Our results indicate that also a slowly recovering, sparse seagrass bed may benefit from additional planting.

**A large restoration scale is even more beneficial in situations with potential bistability: a conceptual framework**

Our study shows strong positive feedback, i.e., at low initial numbers of shoots/seeds (fewer than 1000), the population growth becomes negative. This means that the initial stages of a restoration trial of foundation species may generate bistability, where two alternative and potentially persistent ecosystem regimes are possible (Nystrom et al. 2012). Bistability has been proposed in seagrass systems (e.g., van der Heide et al. 2007, 2008, Carr et al. 2010, 2012). In a framework with alternative stable states, thresholds (tipping points) exist above which self-sustaining feedback promotes recovery (figure 5a). Below the threshold, the planting extirpates, in line with our findings. Note that our findings represent an average situation – individual systems may not show threshold behaviour. From this framework we have demonstrated that, in order to reach a tipping point for recovery it helps to combine (i) increasing the presence of self-facilitating seagrass as a foundation species (vertical wide arrow in Figure 5b and referring to positive density dependence or allee effects, i.e., via reduction of environmental stress by the species engineering activity, Morris & Doak 2002) and (ii) externally reducing the environmental stress (horizontal wide arrow in Figure 5b). Environmental stress has a mean component, and a variance component due to natural variability. The mean component can obviously be reduced by for example habitat rehabilitation and is not related to transplantation scale. The variance component can be tackled by spreading of risks. Spreading of risks is accomplished using large numbers of individuals and hence the spatial extent of the plot, which increases the variability of environmental conditions within the plot and hence the likelihood that favourable conditions are encountered by at least some of the planting (cf. Morris & Doak 2002; our study). Thus, increasing the initial number of shoots/seeds may increase restoration performance via the two pathways that concertedly help to reach the tipping point for recovery in a situation with alternative stable states (figure 5b).



**Acknowledgments**

We thank Prof. dr. G. Borm, Dr. J.C.M. Hendriks and Prof. dr. P. Herman for thorough statistical advice and stimulating discussions, Dr. L. Hanssen for inspiring feedback during all phases of the research, C. Belaire, Dr. I. Yasir and R. Hudson for providing data and K. Giesen, C. Gadouillet and N. Krupski for entering data. A.T. was funded by Greater Caribbean Energy and Environment Foundation grants. N.M. was supported by a Gledden Fellowship from the Institute of Advanced Studies of the University of Western Australia. N.M. C.M.D and A.C. were supported by Biomares contract number LIFE06 NAT/PT/000192. N.M. and C.M.D.

were supported by Opera (FP7, contract number 308393. C.P. and the Cornell Cooperative Extension Marine Program are funded in part by County Executive Steve Bellone and the Suffolk County Legislature, Hauppauge, New York. E.B. and C.L. were funded by University of Pisa (Lardicci 308/ex60%2010). M.L.C and G.A.K were supported by ARC Linkage Grants (LP130100155, LP0454138). This is a contribution to the CSIRO Marine and Coastal Carbon Biogeochemistry Flagship Cluster.

**References cited**

Addy, C.E. (1947) Eel grass planting guide. Maryland Conservationist, 24, 16-17.

Bos, A.R. & van Katwijk, M.M. (2007) Planting density, hydrodynamic exposure and mussel beds affect survival of transplanted intertidal eelgrass. Marine Ecology-Progress Series, 336, 121-129.

Bruno, J.F. & Bertness, M.D. (2001) Positive interactions, faciliations and foundations species. Marine Community Ecology (eds M.D. Bertness, S.D. Gaines & M. Hay), pp. 201-218. Sinauer Associates, Sunderland, Massachusetts, USA.

Cambridge, M.L. & Kendrick, G.A., 2009. Contrasting responses of seagrass transplants (*Posidonia australis*) to nitrogen, phosphorus and iron addition in an estuary. Journal of Experimental Marine Biology and Ecology, 371, 34-41.

Campbell, M.L. (2002) Getting the foundation right: A scientifically based management framework to aid in the planning and implementation of seagrass transplant efforts. Bulletin of Marine Science, 71, 1405-1414.

Cardoso, P.G., Leston, S., Grilo, T.F., Bordalo, M.D., Crespo, D., Raffaelli, D. & Pardal, M.A. (2010) Implications of nutrient decline in the seagrass ecosystem success. Marine Pollution Bulletin, 60, 601-608.

Carr, J., D'Odorico, P., McGlathery, K. & Wiberg, P. (2010) Stability and bistability of seagrass ecosystems in shallow coastal lagoons: Role of feedbacks with sediment resuspension and light attenuation. Journal of Geophysical Research-Biogeosciences, 115, -.

Carr, J.A., D'Odorico, P., McGlathery, K.J. & Wiberg, P.L. (2012) Modeling the effects of climate change on eelgrass stability and resilience: future scenarios and leading indicators of collapse. Marine Ecology Progress Series, 448, 289-301.

Christianen, M.J.A., van Belzen, J., Herman, P.M.J., van Katwijk, M.M., Lamers, L.P.M., van Leent, P.J.M. & Bouma, T.J. (2013) Low-canopy seagrass beds still provide important coastal protection services. Plos One, 8, e62413.

Cunha, A.H., Marba, N.N., van Katwijk, M.M., Pickerell, C., Henriques, M., Bernard, G., Ferreira, M.A., Garcia, S., Garmendia, J.M. & Manent, P. (2012) Changing Paradigms in Seagrass Restoration. Restoration Ecology, 20, 427-430.

Duarte, C.M. (2002) The future of seagrass meadows. Environmental Conservation, 29, 192-206.

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I. & Marbà, M. (2013a) The role of coastal plant communities for climate change mitigation and adaptation. Nature Climate Change, 3, 961-968.

Duarte, C.M., Sintes, T. & Marbà, N. (2013b) Assessing the $CO_2$ capture potential of seagrass restoration projects. Journal of Applied Ecology, 50, 1341-1349.

Fonseca, M.S. (2011) Addy revisited: what has changed with seagrass restoration in 64 years? Ecological Restoration, 29, 73-81.

Fonseca, M.S., Kenworthy, W.J. & Thayer, G.W. (1998) Guidelines for the conservation and restoration of seagrasses in the United States and adjacent waters. NOAA Coastal Ocean Program Decision Analysis Series No. 12. NOAA Coastal Ocean Office, Silver Spring MD.

Greening, H. & Janicki, A. (2006) Toward reversal of eutrophic conditions in a subtropical estuary: Water quality and seagrass response to nitrogen loading reductions in Tampa Bay, Florida, USA. Environmental Management, 38, 163-178.

Hammerli, A. & Reusch, T.B.H. (2002) Local adaptation and transplant dominance in genets of the marine clonal plant *Zostera marina*. Marine Ecology-Progress Series, 242, 111-118.

Hansen, J.C.R. & Reidenbach, M.A. (2012) Wave and tidally driven flows in eelgrass beds and their effect on sediment suspension. Marine Ecology Progress Series, 448, 271-287.

Harrison, F. (2011). Getting started with meta-analysis. Methods in ecology and evolution 2: 1-10

Hemminga, M.A. & Duarte, C.M. (2000) Seagrass Ecology. Cambridge University Press, Cambridge.

Jones, C.G., Lawton, J.H. & Shachak, M. (1994) Organisms As Ecosystem Engineers. Oikos, 69, 373-386.

McArthur, L.C. & Boland, J.W. (2006) The economic contribution of seagrass to secondary production in South Australia. Ecological Modelling, 196, 163-172.

McGlathery, K.J., Reynolds, L.K., Cole, L.W., Orth, R.J., Marion, S.R. & Schwarzschild, A. (2012) Recovery trajectories during state change from bare sediment to eelgrass dominance. Marine Ecology Progress Series, 448, 209-221.

McLeod, E., Chmura, G.L., Bouillon, S., Salm, R., Bjork, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H. & Silliman, B.R. (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment, 9, 552-560.

Morris, W.F. & Doak, D.F. (2002) Quantitative conservation biology. Theory and practice of population viability analysis. Sinauer Associates, Sunderland, Massachusetts, USA.

Orth, R.J., Carruthers, T.J.B., Dennison, W.C., Duarte, C.M., Fourqurean, J.W., Heck, K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Olyarnik, S., Short, F.T., Waycott, M. & Williams, S.L. (2006) A global crisis for seagrass ecosystems. BioScience, 56, 987-996.

Orth, R.J., Moore, K.A., Marion, S.R., Wilcox, D.J. & Parrish, D.B. (2012) Seed addition facilitates eelgrass recovery in a coastal bay system. Marine Ecology Progress Series, 448, 177-195.

Paling, E.I., Fonseca, M., van Katwijk, M.M. & van Keulen, M. (2009) Seagrass restoration. (eds G. Perillo, E. Wolanski, D. Cahoon & M. Brinson), pp. 687-713. Elsevier, Amsterdam.

Paling, E.I., van Keulen, M., Wheeler, K.D., Phillips, J., Dyhrberg, R. & Lord, D.A. (2001) Improving mechanical seagrass transplantation. Ecological Engineering, 18, 107-113.

Phillips, R.C. (1980) Transplanting methods. (eds R.C. Phillips & C.P. McRoy), pp. 41-56. Garland Press, New York.

Schulte, D.M., Burke, R.P. & Lipcius, R.N. (2009) Unprecedented restoration of a native oyster metapopulation. Science, 325, 1124-1128

Short, F.T., Davis, R.C., Kopp, B.S., Short, C.A. &Burdick, D.M. (2002) Site-selection model for optrimal transplantation of eegrass *Zostera marina* in the Northeastern US. Marine Ecology-Progress Series, 227, 253-267

Sinclair, E.A., Verduin, J.J., Krauss, S.L., Hardinge, J., Anthony, J. & Kendrick, G.A. (2013) A genetic assessment of a successful seagrass meadow (*Posidonia australis*) restoration trial. Ecological Management and Restoration, 14, 68-71.

Suykerbuyk, W., Govers, L.L., Bouma, T.J., Giesen, W.B.J.T., de Jong, D.J., van de Voort, R., Giesen, K., Giesen, P.T. & van Katwijk M.M. (submitted) External forcing and stochastic processes rather than positive feedbacks determine seagrass transplantation success in a dynamic, intertidal environment.

Thorhaug, A. (1974) Transplantation of the seagrass *Thalassia testudinum* Koenig. Aquaculture, 4, 177-183.

Thorhaug, A. (1981) Biology and Management of Seagrass in the Caribbean. Ambio, 10, 295-298.

Thorhaug, A., Raven, J. & Franklin, L. (2009) Carbon cycling and sequestration in the sea by marine macrophytes. Plant Science Bulletin, 55, 156-162.

Unsworth, R.K.F., Cullen, L.C., Pretty, J.N., Smith, D.J. & Bell, J.J. (2010) Economic and subsistence values of the standing stocks of seagrass fisheries: Potential benefits of no-fishing marine protected area management. Ocean & Coastal Management, 53, 218-224.

Valdemarsen, T., Wendelboe, K., Egelund, J.T., Kristensen, E. & Flindt, M.R. (2011) Burial of seeds and seedlings by the lugworm *Arenicola marina* hampers eelgrass (*Zostera marina*) recovery. Journal of Experimental Marine Biology and Ecology, 410, 45-52.

van der Heide, T., Smolders, A., Rijkens, B., van Nes, E.H., van Katwijk, M.M. & Roelofs, J. (2008) Toxicity of reduced nitrogen in eelgrass (*Zostera marina*) is highly dependent on shoot density and pH. Oecologia, 158, 411-419.

van der Heide, T., van Nes, E.H., Geerling, G.W., Smolders, A.J.P., Bouma, T.J. & van Katwijk, M.M. (2007) Positive feedbacks in seagrass ecosystems: implications for success in conservation and restoration. Ecosystems, 10, 1311-1322.

van der Heide, T., van Nes, E.H., van Katwijk, M.M., Olff, H. & Smolders, A.J.P. (2011) Positive feedbacks in seagrass ecosystems - evidence from large-scale empirical data. Plos One, 6.

van Katwijk, M.M., Bos, A.R., de Jonge, V.N., Hanssen, L.S.A.M., Hermus, D.C.R. & de Jong, D.J. (2009) Guidelines for seagrass restoration: importance of habitat selection and donor population, spreading of risks, and ecosystem engineering effects. Marine Pollution Bulletin, 58, 179-188.

Vaudrey, J.M.P., Kremer, J.N., Branco, B.F. & Short, F.T. (2010) Eelgrass recovery after nutrient enrichment reversal. Aquatic Botany, 93, 237-243.

Watson, R.A., Coles, R.G. & Long, W.J.L. (1993) Simulation estimates of annual yield and landed value for commercial penaeid prawns from a tropical seagrass habitat, northern Queensland, Australia. Australian Journal of Marine and Freshwater Research, 44, 211-219.

Waycott, M., Duarte, C.M., Carruthers, T.J.B., Orth, R.J., Dennison, W.C., Olyarnik, S., Calladine, A., Fourqurean, J.W., Heck, K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Short, F.T. & Williams, S.L. (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences of the United States of America, 106, 12377-12381.

**Figure legends**

Figure 1. Map of 1786 trials analysed (green dots represent trials). Frequency diagrams of the initial scale of the restoration trials per bioregion show that most trials start with less than 1000 shoots. Blue lines separate the bioregions.

Figure 2. Performance of seagrass restoration trials in relation to cause of decline prior to planting, distance from and recovery of the donor site and plant material and anchoring techniques. The semi-quantitative integrated succes score and its standard error of the mean were calculated from initial survival and long-term performance after initial survival, see materials and methods. The categories for causes of decline and anchoring techniques are elaborated in table 2 and 3 respectively. Rhiz.fr. = rhizome fragments

Figure 3. Positive effects of restoration scale (number of initially planted shoots) on the trial survival and population growth rate of seagrass in survived trials. (a) Kaplan-Meier-estimated trial survival after ≥ 23 months, ± confidence interval (proportional hazard model over entire period: $p=0.0070$); (b) Log mean population growth rate (log of increase in number of shoots $mo^{-1}$) ± standard error of the mean, ANOVA $p<0.0001$, $df=4$.

Figure 4. Framework depicting the synergy to investing in spatial extent and planting density, and the trade-off, given a high but limited number of plants, to invest relatively more in either spatial extent or in planting density. A large investment in high numbers may be needed for best restoration practice in dynamic systems to capture windows of opportunity generated by spatial heterogeneity (horizontal axis: spreading of risks, or spatial extent of planting, $m^2$) and to reach threshold required to initiate self-sustaining feedback (vertical

axis: recovery of feedback, or planting density, $m^{-2}$). Knowledge of the local environment is essential to choose the best planting strategy.

Figure 5. How large initial numbers of foundation individuals (i.e., a large-scale restoration) are particularly needed when alternative stable states are likely and a critical threshold needs to be crossed, as in our study object. (a) Situation with alternative stable states. The dotted line indicates tipping points for recovery and collapse: above this line self-sustaining feedback propellers the system to high presence of the foundation species through natural recovery. Below this line the system will collapse towards a state without the foundation species. (b) How reintroduction (vertical arrow) and stress reduction (horizontal arrow) concertedly help to reach a tipping point for recovery. Large numbers of initial numbers of foundation individuals considerably increase the chance to reach a tipping point for recovery, via dual action: (i) obviously the reintroduction itself is scale dependent due to positive feedback, but also (ii) large numbers are needed to overcome the variable and stochastic part of environmental stress (left part of horizontal arrow, indicated by 'var'), by spreading of risks in time and space.

Supporting Information.

Additional Supporting Information may be found in the online version of this article:

Appendix S1: Sources for the dataset

Table S1: Effect of species and environmental characteristics on restoration performance.

Table S2: Effect of planting techniques on restoration performance

Table S3: Tests for confounding effects

Figure S1: Numbers per decade and learning curve of seagrass restoration trials

Table 1. Overview of results and characteristics of the trials. Phase 1 ≤ 9 months, phase 2: 10-22 months and phase 3 ≥ 23 months. The number of samples (N) depended on the availability of the data.

| | N | median | min | max |
|---|---|---|---|---|
| number of shoots at t=0 | 1109 | 409 | 2 | 3E+06 |
| standardised area at t=0 ($m^2$)[a] | 1108 | 0.93 | 0.001 | 5730 |
| number of shoots of surviving trials at t=t | 487 | 720 | 0.43 | 3.E+09 |
| standardised area of surviving trials at t=t ($m^2$) | 487 | 1.26 | 0.0001 | 9.E+06 |
| monitoring time t (months) | 1715 | 12 | 0.70 | 456 |
| growth rate* of surviving trials ($months^{-1}$) | 486 | -0.005 | -2.996 | 1.251 |
| population growth rate phase 1 | 189 | -0.082 | -2.996 | 1.251 |
| population growth rate phase 2 | 173 | 0.025 | -0.453 | 0.406 |
| population growth rate phase 3 | 124 | 0.029 | -0.354 | 0.245 |

| | N | % | Median monitoring time (months) |
|---|---|---|---|
| overall trial survival** | | 37 % | |
| trial survival phase 1 | 1034 | 70 % | 5.7 |
| trial survival phase 2 | 677 | 67 % | 12 |
| trial survival phase 3 | 412 | 79 % | 36 |

[a] Areal extent ($m^2$) was estimated from the standardised area per species (saps), which was calculated from the average diameter of the area that a shoot occupies (spacer length, sl)

per species (Marbà and Duarte 1998) and multiplied by the number of shoots (nsh): saps = nsh x π x (½sl)$^2$.

*Growth rate refers to increase in number of shoots .

**The overall trial survival refers to the survival of trials, not shoots, and has been estimated by multiplying the actual trial survival rates within each of the three phases, i.e. 70% x 67% x 79% (note that most trials have only one or two monitoring dates).

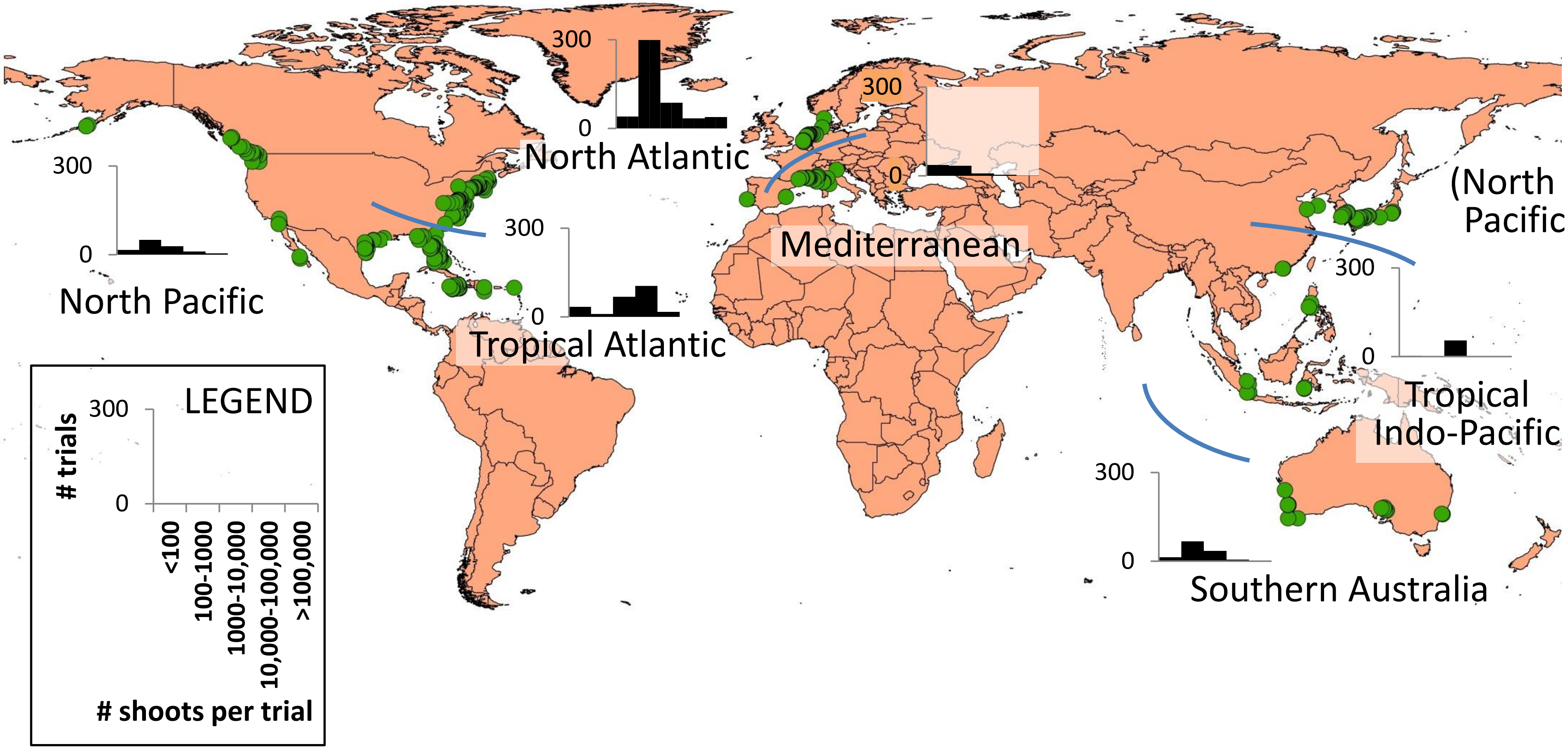
Table 2. Classification of causes of decline of the meadows in the area of the restoration trial

| Main target of disturbance | Types of disturbance | Impact |
|---|---|---|
| Local direct impact | Trawl fishing | Mechanical damage & removal |
| | Boat/vessel damage | |
| | Dumping | |
| | Mining in meadow | |
| Water quality | Thermal pollution | Heat stress |
| | Eutrophication | Nutrient stress / algal overgrowth / sulfide toxicity |
| | Oil or chemical pollution | Chemical impact |
| | Turbidity increase | Lack of light |
| Substrate | Dredging | Temporary increased turbidity |
| | Filling | Smothering (by sediment) |
| | Erosion (of seagrass bed sediment) | Temporary increased sediment dynamics |
| | | Changes in sediment type (e.g. replacement by less favourable sediment) |
| Natural cause | Wasting disease | Infection, thinning, mortality |
| | Storms | Unstable sediment, loss of anchoring |
| | Beach erosion | |
| | Overwash | |
| Construction | Large scale construction (e.g. sea walls, ports, bridges); reclamation | Removal of part or entire seagrass meadow |

Table 3. Categories of anchoring techniques and plant material as distinguished in this study

Anchoring technique categories: **weights** are provided by rocks, shells, bricks or sandbags and include the TERFS method: Transplanting Eelgrass Remotely with Frame System (Short et al. 2002); **staples** include rods, bamboo’s, pegs, sprigs and washers; **frames** include anchoring techniques that attach the planting material to frames, grids, quadrates, nets, mats or meshes that are not weighted and do not include TERFS.

Plant material comprise the categories **sods:** intact units of native sediment with roots, rhizomes and leaves, sometimes also referred to as plugs and peat pots (the latter are only included here if the sediment is included in the transplantation), **rhizome fragments** with shoots, also sometimes referred to as turions or sprigs; **seeds** and **seedlings.**


North Atlantic
300
0
North Pacific
300
0
Tropical Atlantic
300
0
Mediterranean
300
0
(North Pacific)
Tropical Indo-Pacific
300
0
Southern Australia
300
0
LEGEND
# trials
300
0
<100
100-1000
1000-10,000
10,000-100,000
>100,000
# shoots per trial

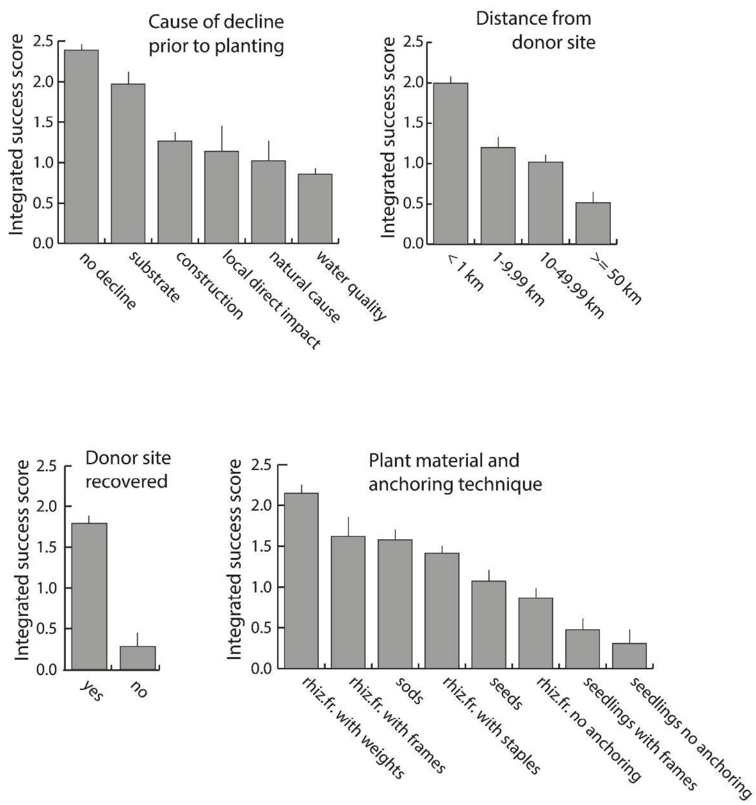



Figure 2. Performance of seagrass restoration trials in relation to cause of decline prior to planting, distance from and recovery of the donor site and plant material and anchoring techniques. The semi-quantitative integrated succes score and its standard error of the mean were calculated from initial survival and long-term performance after initial survival, see materials and methods. The categories for causes of decline and anchoring techniques are elaborated in table 2 and 3 respectively. Rhiz.fr. = rhizome fragments
297x420mm (300 x 300 DPI)

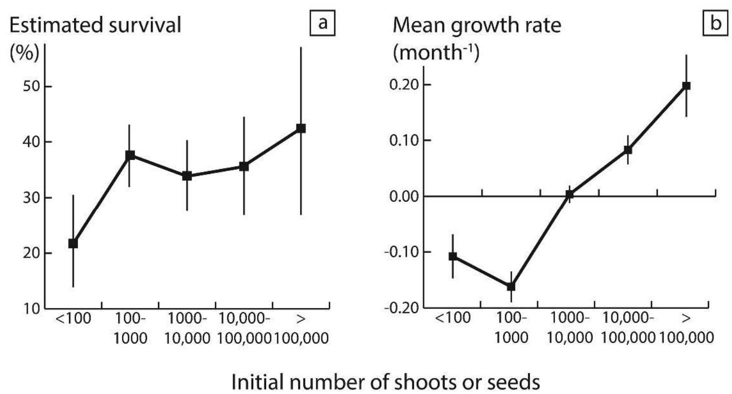



Figure 3. Positive effects of restoration scale (number of initially planted shoots) on the trial survival and population growth of seagrass in survived trials. (a) Kaplan-Meier-estimated trial survival after ≥ 23 months, ± confidence interval (proportional hazard model over entire period: $p=0.0070$); (b) Mean population growth rate (increase in number of shoots mo-1) ± standard error of the mean, ANOVA $p<0.0001$, $df=4$.
297x420mm (300 x 300 DPI)

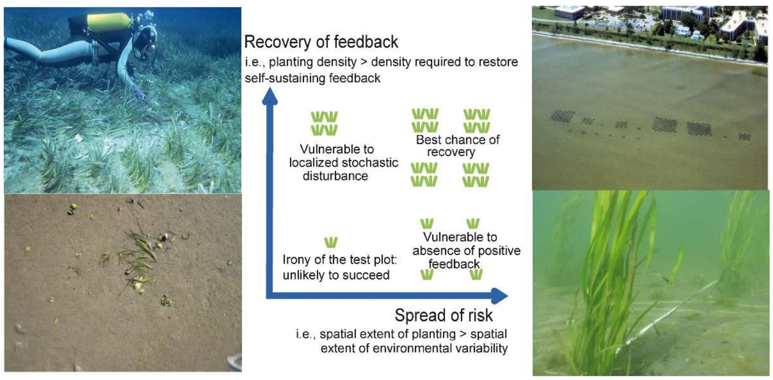



Figure 4. Framework depicting the trade-off to investing in either planting density or spatial extent, and the synergy to invest in both. A large investment in high numbers may be needed for best restoration practice in dynamic systems to capture windows of opportunity generated by spatial heterogeneity (horizontal axis: spreading of risks, or spatial extent of planting, m2) and to reach threshold required to initiate self-sustaining feedback (vertical axis: recovery of feedback, or planting density, m-2). Knowledge of the local environment is essential to choose the best planting strategy.
297x420mm (300 x 300 DPI)

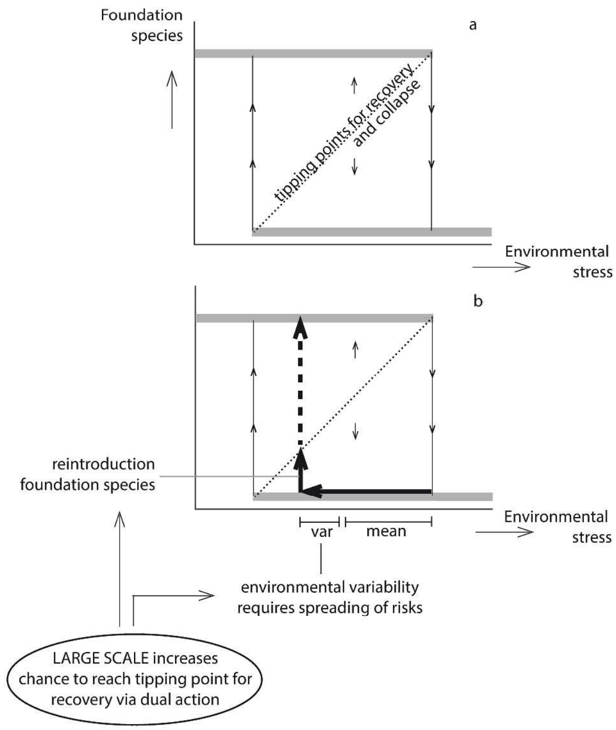



Figure 5. How large initial numbers of foundation individuals (i.e., a large-scale restoration) are particularly needed when alternative stable states are likely and a critical threshold needs to be crossed, as in our study object. (a) Situation with alternative stable states. The dotted line indicates tipping points for recovery and collapse: above this line self-sustaining feedback propellers the system to high presence of the foundation species through natural recovery. Below this line the system will collapse towards a state without the foundation species. (b) How reintroduction (vertical arrow) and stress reduction (horizontal arrow) concertedly help to reach a tipping point for recovery. Large numbers of initial numbers of foundation individuals considerably increase the chance to reach a tipping point for recovery, via dual action: (i) obviously the reintroduction itself is scale dependent due to positive feedback, but also (ii) large numbers are needed to overcome the variable and stochastic part of environmental stress (left part of horizontal arrow, indicated by ‘var’), by spreading of risks in time and space.
297x420mm (300 x 300 DPI)

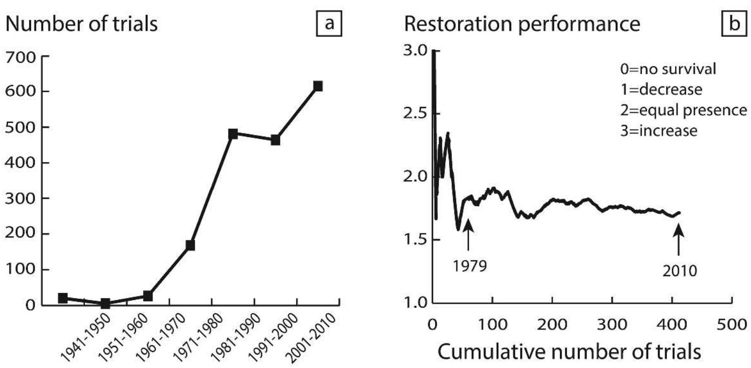



Figure S1. Despite increasing numbers of seagrass restoration trials initiated per decade, accumulated experience has not yet improved the performance of subsequent trials. (a) Increase of numbers of reviewed trials during the last 8 decades (2 trials initiated in 2011 are not depicted); (b) Learning curve: the average restoration performance score (representing the 415 trials monitored >22 months, scores 0=no trial survival, 1=decrease, 2=equal presence and 3=increase) as function of the cumulative number of trials since 1972 remains low after some initial fluctuations.

Learning curve
297x420mm (300 x 300 DPI)

Supplementary Information Table S1. Restoration success in relation to general and environmental characteristics. Initial trial survival (< 10 months, scores 0=no survival and 1=survival) and long term trial success (>22 months, scores 0=no survival, 1=decrease, 2=equal presence and 3=increase) in relation to general characteristics, plant and environmental characteristics and planting techniques. Integrated success score is the multiplication of initial trial survival and long term trial success. Logistic regression of initial trial survival and anova p-values of long term trial success are presented per variable. Number of plantings (N) and estimated mean scores are presented per category with differing letters in superscript denoting logistic regression contrasts in initial trial survival and Tukey posthoc significant differences in long term trial success at an alpha level of 0.05.

| | Initial trial survival (< 10 months) | | Long term trial success (> 22 months) | | integrated success score |
|---|---|---|---|---|---|
| Variable | N | p-value and estimated mean | N | p-value and estimated mean | |
| Reason for planting | | <0.0001 | | 0.0185 | |
| restore natural values | 318 | $0.53^{B}$ | 119 | $1.49^{B}$ | 0.79 |
| mitigation | 90 | $0.86^{A}$ | 138 | $1.80^{AB}$ | 1.55 |
| research | 275 | $0.91^{A}$ | 123 | $1.65^{B}$ | 1.50 |
| test plots | 218 | $0.58^{B}$ | 24 | $2.25^{A}$ | 1.31 |
| Source | | 0.0055 | | 0.0004 | |
| grey literature | 395 | $0.73^{A}$ | 213 | $1.92^{A}$ | 1.40 |

| | | | | | |
|---|---|---|---|---|---|
| web of science | 632 | $0.65^{B}$ | 201 | $1.50^{B}$ | 0.98 |
| Cause of decline[1] | | <0.0001 | | <0.0001 | |
| no decline | 103 | $0.92^{A}$ | 22 | $2.59^{A}$ | 2.38 |
| substrate | 60 | $0.85^{AB}$ | 31 | $2.32^{AB}$ | 1.97 |
| construction | 132 | $0.81^{B}$ | 110 | $1.56^{B}$ | 1.26 |
| local direct impact | 36 | $0.69^{BC}$ | 14 | $1.64^{B}$ | 1.13 |
| natural cause | 68 | $0.56^{C}$ | 12 | $1.83^{AB}$ | 1.02 |
| water quality | 475 | $0.56^{C}$ | 144 | $1.53^{B}$ | 0.86 |
| Removal of threats | | 0.0043 | | <0.0001 | |
| no threats | 93 | $0.92^{A}$ | 22 | $2.59^{A}$ | 2.41 |
| complete removal | 30 | $0.70^{B}$ | 26 | $2.39^{A}$ | 1.67 |
| partial removal | 344 | $0.78^{B}$ | 157 | $1.62^{B}$ | 1.26 |
| Distance from donor site | | <0.0001 | | <0.0001 | |
| < 1 km | 151 | $0.74^{B}$ | 46 | $2.70^{A}$ | 2.00 |
| 1-9.99 km | 103 | $0.88^{A}$ | 70 | $1.36^{B}$ | 1.20 |
| 10-49.99 km | 324 | $0.66^{B}$ | 92 | $1.54^{B}$ | 1.02 |
| >= 50 km | 155 | $0.32^{C}$ | 44 | $1.64^{B}$ | 0.52 |
| Donor site recovered | | <0.0001 | | <0.0001 | |
| yes | 217 | $0.88^{A}$ | 111 | $2.05^{A}$ | 1.80 |
| no | 68 | $0.31^{B}$ | 22 | $0.91^{B}$ | 0.28 |
| Bioturbation was a factor | | 0.0005 | | <0.0001 | |

| | | | | | |
|---|---|---|---|---|---|
| no | 258 | 0.78$^{A}$ | 116 | 2.05$^{A}$ | 1.60 |
| yes | 28 | 0.46$^{B}$ | 42 | 1.71$^{B}$ | 0.79 |
| Depth | | <0.0001 | | 0.0014 | |
| 0-0.49 m | 169 | 0.55$^{C}$ | 51 | 1.29$^{B}$ | 0.71 |
| 0.5-0.99 m | 175 | 0.45$^{C}$ | 20 | 2.20$^{A}$ | 0.99 |
| 1-1.99 m | 195 | 0.69$^{B}$ | 71 | 1.48$^{AB}$ | 1.02 |
| 2-3.99 m | 112 | 0.86$^{B}$ | 37 | 2.05$^{A}$ | 1.76 |
| >4 m | 97 | 0.93$^{A}$ | 80 | 1.30$^{B}$ | 1.21 |
| Emergence | | <0.0001 | | <0.0001 | |
| subtidal | 702 | 0.72$^{A}$ | 318 | 1.88$^{A}$ | 1.35 |
| intertidal | 238 | 0.50$^{B}$ | 84 | 1.05$^{B}$ | 0.53 |

[1]Explanation see Table 2.

Supplementary Information Table S2. Restoration success in relation to planting procedures. Explanation see table S1.

| | Initial trial survival (< 10 months) | | Long term trial success (> 22 months) | | integrated success score |
|---|---|---|---|---|---|
| Variable | N | p-value and estimated mean | N | p-value and estimated mean | |
| Anchoring technique[1] | | <0.0001 | | <0.0001 | |
| weight (including TERFS) | 106 | 0.76$^{A}$ | 35 | 2.69$^{A}$ | 2.07 |
| staple | 301 | 0.79$^{A}$ | 129 | 1.78$^{B}$ | 1.41 |
| none | 417 | 0.52$^{B}$ | 142 | 1.73$^{B}$ | 0.95 |
| frame | 93 | 0.82$^{A}$ | 54 | 0.93$^{C}$ | 0.76 |
| Type of plant material[1] | | <0.0001 | | <0.0001 | |
| sods | 149 | 0.79$^{A}$ | 116 | 1.79$^{A}$ | 1.41 |
| rhizome fragments | 570 | 0.71$^{A}$ | 210 | 1.90$^{A}$ | 1.35 |
| seeds | 88 | 0.58$^{B}$ | 22 | 1.77$^{A}$ | 1.03 |
| seedlings | 179 | 0.55$^{B}$ | 49 | 0.67$^{B}$ | 0.37 |
| Anchoring technique combined with plant material[1] | | <0.0001 | | <0.0001 | |

| | | | | | |
|---|---|---|---|---|---|
| rhizome fragments + weights | 85 | 0.78$^{A}$ | 34 | 2.77$^{A}$ | 2.16 |
| rhizome fragments + frames | 39 | 0.87$^{A}$ | 14 | 1.86$^{B}$ | 1.62 |
| sods (no anchoring) | 103 | 0.85$^{A}$ | 71 | 1.85$^{B}$ | 1.57 |
| rhizome fragments + staples | 283 | 0.81$^{A}$ | 115 | 1.76$^{B}$ | 1.43 |
| seeds (no anchoring) | 80 | 0.55$^{B}$ | 20 | 1.95$^{AB}$ | 1.07 |
| rhizome fragments (no anchoring) | 148 | 0.45$^{B}$ | 32 | 1.91$^{AB}$ | 0.86 |
| seedlings + frames | 35 | 0.8$^{A}$ | 32 | 0.59$^{C}$ | 0.47 |
| seedlings (no anchoring) | 112 | 0.43$^{B}$ | 14 | 0.71$^{C}$ | 0.31 |
| Fertilization | | <0.0001 | | 0.0021 | |
| fertilized | 83 | 0.92$^{A}$ | 9 | 2.89$^{A}$ | 2.66 |
| not fertilized | 931 | 0.66$^{B}$ | 391 | 1.66$^{B}$ | 1.10 |
| Planting method | | 0.0325 | | 0.008 | |
| manual | 601 | 0.69$^{B}$ | 290 | 1.88$^{A}$ | 1.30 |
| mechanical | 41 | 1.00$^{A}$ | 34 | 1.35$^{B}$ | 1.35 |
| Habitat manipulation | | 0.0004 | | <0.0001 | |
| none | 428 | 0.71$^{B}$ | 215 | 2.03$^{A}$ | 1.44 |
| anti-bioturbation measures | 21 | 1.00$^{A}$ | 15 | 1.33$^{B}$ | 1.33 |
| sediment stabilisation | 59 | 0.80$^{AB}$ | 28 | 0.50$^{C}$ | 0.40 |
| Protection measures | | <0.0001 | | 0.2433 | |
| none | 419 | 0.72$^{A}$ | 240 | 1.87 | 1.35 |
| against hydrodynamics | 34 | 0.35$^{B}$ | 7 | 1.57 | 0.55 |

| | | | | | |
|---|---|---|---|---|---|
| against grazing | 18 | $0.33^{B}$ | 12 | 1.33 | 0.44 |

[1]Explanation of categories, see Table 3

Supplementary Information Table S3. Tests for confounding effects. Relationship between initial number of shoots (log-transformed) and 15 trial characteristics (listed in column 1) is depicted in column 4 by the average number of shoots after log-transformation; the p-value and Tukey posthoc tests (alpha level of 0.05) show significant number of shoots between categories. Differing letters in superscript denote Tukey posthoc significant differences at an alpha level of 0.05. The number of trial (N) are presented in column 3. The correlation between integrated success score (column 2, see Table S1 and S2) and estimated mean number of shoots per category (column 4) is presented in column 5. Only trials were included that also evaluated the number of shoots at the end of monitoring) are presented per category. There are no confounding effects as the correlation coefficients are all negative or near zero.



| | Integrated success score | | Initial planting scale log (number of shoots) | potential confounding effects |
|---|---|---|---|---|
| Characteristics | | N | p-value and estimated mean | Correlation coefficient |
| Seagrass species | | | >0.0001 | -0.55 |
| *Posidonia australis* | 2.71 | 19 | $6.34^{AB}$ | |
| *Posidonia oceanica* | 1.68 | 51 | $4.77^{B}$ | |
| *Halodule wrightii* | 1.36 | 58 | $8.74^{AB}$ | |
| *Zostera marina* | 1.18 | 202 | $6.44^{AB}$ | |
| *Posidonia sinuosa* | 1.01 | 5 | $8.52^{AB}$ | |
| *Syringodium filiforme* | 0.98 | 17 | $9.78^{A}$ | |
| *Zostera noltii* | 0.92 | 27 | $7.67^{AB}$ | |

| | | | | |
|---|---|---|---|---|
| *Thalassia testudinum* | 0.83 | 51 | 8.12^AB | |
| *Amphibolis antarctica* | 0.63 | 1 | 6.22^AB | |
| Reason for planting | | | <0.0001 | -0.25 |
| restore natural values | 0.79 | 41 | 8.31^A | |
| mitigation | 1.55 | 105 | 8.82^A | |
| research | 1.50 | 152 | 4.83^C | |
| test plots | 1.31 | 96 | 7.06^B | |
| Cause of decline[1] | | | <0.0001 | -0.46 |
| no decline | 2.38 | 57 | 4.77^C | |
| substrate | 1.97 | 95 | 9.05^A | |
| construction | 1.26 | 102 | 6.14^BC | |
| local direct impact | 1.13 | 22 | 9.58^A | |
| natural cause | 1.02 | 16 | 9.41^A | |
| water quality | 0.86 | 147 | 7.1^B | |
| Removal of threats | | | <0.0001 | -0.79 |
| no threats | 2.41 | 54 | 4.73^C | |
| complete removal | 1.67 | 35 | 8.94^A | |
| partial removal | 1.26 | 213 | 7.66^B | |
| Distance from donor site | | | 0.0004 | 0.15 |
| < 1 km | 2.00 | 118 | 8.01^A | |
| 1-9.99 km | 1.20 | 69 | 7.26^AB | |
| 10-49.99 km | 1.02 | 114 | 6.66^B | |
| >= 50 km | 0.52 | 43 | 8.05^A | |
| Donor site recovered | | | n.s. | |
| yes | 1.80 | 260 | 7.96 | |
| no | 0.28 | 14 | 8.49 | |

| | | | | |
|---|---|---|---|---|
| Bioturbation was a factor | | | 0.0002 | -1.0 |
| no | 1.60 | 284 | $7.61^{B}$ | |
| yes | 0.79 | 10 | $10.63^{A}$ | |
| Depth | | | <0.0001 | -0.18 |
| 0-0.49 m | 0.71 | 29 | $6.6^{B}$ | |
| 0.5-0.99 m | 0.99 | 34 | $9.61^{A}$ | |
| 1-1.99 m | 1.02 | 105 | $8.41^{A}$ | |
| 2-3.99 m | 1.76 | 93 | $7.07^{B}$ | |
| >4 m | 1.21 | 79 | $5.16^{C}$ | |
| Emergence | | | N.S. | |
| subtidal | 1.35 | 377 | 7.59 | |
| intertidal | 0.53 | 42 | 7.02 | |
| Anchoring technique[2] | | | <0.0001 | -0.13 |
| weight (including TERFS) | 2.07 | 84 | $6.52^{B}$ | |
| staple | 1.41 | 133 | $5.25^{C}$ | |
| none | 0.90 | 202 | $8.96^{A}$ | |
| frame | 0.76 | 32 | $5.2^{C}$ | |
| Type of plant material[2] | | | <0.0001 | 0.023 |
| sods | 1.41 | 79 | $9.04^{B}$ | |
| rhizome fragments | 1.35 | 329 | $6.59^{C}$ | |
| seeds | 1.03 | 16 | $11.97^{A}$ | |
| seedlings | 0.92 | 37 | $6.62^{C}$ | |
| Anchoring technique combined with plant material[2] | | | <0.0001 | 0.01 |
| rhizome fragments + weights | 2.16 | 73 | $6.70^{ED}$ | |
| rhizome fragments + frames | 1.62 | 24 | $4.81^{F}$ | |

| | | | | |
|---|---|---|---|---|
| sods (no anchoring) | 1.57 | 67 | $9.29^{B}$ | |
| rhizome fragments + staples | 1.43 | 131 | $5.24^{EF}$ | |
| seeds (no anchoring) | 1.07 | 16 | $11.97^{A}$ | |
| rhizome fragments (no anchoring) | 0.86 | 93 | $8.65^{CB}$ | |
| seedlings + frames | 0.47 | 5 | $3.99^{F}$ | |
| seedlings (no anchoring) | 0.31 | 25 | $7.24^{CD}$ | |
| Fertilization | | | <0.0001 | -1.00 |
| fertilized | 2.66 | 54 | $5.73^{B}$ | |
| not fertilized | 1.10 | 429 | $7.36^{A}$ | |
| Planting method | | | n.s. | - |
| manual | 1.30 | 324 | 7.89 | |
| mechanical | 1.35 | 20 | 9.05 | |
| Habitat manipulation | | | n.s. | |
| none | 1.44 | 332 | 7.52 | |
| anti-bioturbation measures | 1.33 | 11 | 9.45 | |
| sediment stabilisation | 0.40 | 6 | 8.03 | |
| Protection measures | | | n.s. | |
| none | 1.35 | 319 | 7.54 | |
| against hydrodynamics | 0.55 | 8 | 6.69 | |
| against grazing | 0.44 | 5 | 7.03 | |

[1]Categories are explained in Table 2

[2]Categories are explained in Table 3

**Supplementary material s1**

**Supporting Information Appendix S1. Sources for the dataset. Data accessibility: data are intended to be stored at Radboud University Repository**


1. Addy CE & Aylward DA (1944) Status of eelgrass in Massachusetts during 1943. *Journal of Wildlife Management* 8:7.
2. Association for shore environment creation (2009) *Report for a promotion project of public-private collaboration* pp 1-33.
3. Avery W & Johansson R (2006) Experimental *Halodule wrightii* and *Syringodium filiforme* transplanting in Hillsborough Bay, Florida. *Seagrass restoration: success, failure, and the cost of both*, eds Treat SF & Lewis RR (Lewis Environmental Services, Inc., Valrico, USA, Mote Marine Laboratory, Sarasota, March 11-12, 2003), pp 91-102.
4. Baca B, Stone GW, & Snachez-Gomez A (2006) Cultivation studies of the *Halophila* seagrasses *H. johnsonii* and *H. decipiens. Seagrass restoration: success, failure, and the cost of both*, eds Treat SF & Lewis RR (Lewis Environmental Services, Inc., Valrico, USA, Mote Marine Laboratory, Sarasota, March 11-12, 2003), pp 147-154.
5. Balestri E (2001) *Approfondimento della struttura della prateria a Posidonia oceanica e delle principali biocenosi associate: valutazione di progetti di recupero dell'area antistante lo stabilimento Solvay* pp 1-115.
6. Balestri E, Piazzi L, & Cinelli F (1998) Survival and growth of transplanted and natural seedlings of *Posidonia oceanica* (L.) Delile in a damaged coastal area. *Journal of Experimental Marine Biology and Ecology* 228(2):209-225.
7. Bastyan GR & Cambridge ML (2008) Transplantation as a method for restoring the seagrass *Posidonia australis*. *Estuarine Coastal And Shelf Science* 79(2):289-299.

8. Belaire Consulting I (1990) North Marina, Inc., Corps of Engineers Permit No. 17075, Mitigation monitoring. (Copano Bay, Texas).

9. Belaire Consulting I (1990) Pelone Island Mitigation, March 1990 Monitoring report, Corps of Engineers Permit No. 127669. (Nueces County, Texas).

10. Belaire Consulting I (1992) Monitoring of Seagrass Mitigation, Bright and Company, Corps of Engineers Permit No. 18957. (Laguna Madre, Texas).

11. Belaire Consulting I (1992) Fall 1992 Seagrass Monitoring Survey, 44.5-Acre Restoration. (Lower Laguna Madre, Texas).

12. Belaire Consulting I (1993) TOMCAT Project, Three-Year Monitoring Survey, Seagrass Restoration and Spartina alterniflora Planting, Matagorda Bay. (Matagorda Bay, Texas).

13. Belaire Consulting I (1993) Seagrass Monitoring Survey, 20" Pipelin, Upper Laguna Madre. (Upper Laguna Madre, Texas).

14. Belaire Consulting I (1995) Three-Year Monitoring of Central Power and Light Company 1.0-acre Seagrass Mitigation Site. (South Padre Island, Texas).

15. Belaire Consulting I (1998) Three-year monitoring survey, 0.492-acre seagrass mitigation site. Oleander Point, Upper Laguna Madre, Texas, USA. Submitted to City of Corppus Christi, 5 May 1998.

16. Belaire Consulting I (1998) Three-year seagrass monitoring survey, Oleander Point mitigaion, unplanted scrapedown area, Upper Laguna Madre, Texas, USA. Submitted to City of corpus Christi, 5 May 1998.

17. Belaire Consulting I (1998) Three-year monitoring, six-acre seagrass restoration, Upper Laguna Madre, Texas, USA. Submitted to LeBouf Brothers Towing, 15 May 1998.

18. Belaire Consulting I (1998) Three-year seagrass coverage monitoring survey, 21.37-acre mitigation site, Demit Pier Project, Dermit Pier, North Padre Island, Nuences County,

Texa, USA. Submitted to City of Corpus Christi, 15 May 1998.

19. belaire Consulting I (2006) Two-year monitoring report mitigation project, Lower Laguna Madre, Laguna Vista, Cameron County, Texas, USA. Submitted to South Padre Island Develoopment Company.

20. Belaire Consulting I (2007) Five-year monitoring seagrass and smooth cordgrass mitigation area, Redfish Bay, Aransas Pass, San Patricio/Aransas/Nuences Counties, Texas, USA. Submitted to Kiewit Offshore Services, LTD, 6 Dec. 2007.

21. Belaire Consulting I (2010) Report of findings fo a post-planting survival/vegetation coverage monitoring survey of a 3.31 acre seagrass restoration area in the Upper Laguna Mader, Port Lavaca, Calhoun County, Texas, USA. Submitted to T.W. LaQuay Dredging Inc., 16 Nov. 2010.

22. Belaire Consulting I (2011) Two-year monitoring seagrass, Smooth Cordgrass, Black Mangrove and Saltwort mitigation area for permit no. SWG-2006-00408, Port Isabel, Cameron County, Texas, USA. Submitted to Subsea7 Inc., 6 Oct. 2011.

23. Bell SS, Clements LAJ, & Kurdziel J (1993) Production in natural and restored seagrasses: A case study of a macrobenthic polychaete. *Ecological Applications* 3:610-621.

24. Bell SS, Tewfik A, Hall MO, & Fonseca MS (2008) Evaluation of seagrass planting and monitoring techniques: Implications for assessing restoration success and habitat equivalency. *Restoration Ecology* 16(3):407-416.

25. Bird KT, Jewett-Smith J, & Fonseca MS (1994) Use of in vitro propagated *Ruppia maritima* for seagrass meadow restoration. *Journal of Coastal Research* 10:732-737.

26. Bloom SA (1987) Seagrass zonation: test of competition and disturbance at Seahorse Key, Florida. *Proceedings of the 14th Annual Conference on Wetlands Restoration and*

*Creation.* , ed Webb FJ (Hillsborough Community College, Tampa, Florida, USA), pp 48-62.

27. Bologna PAX & Sinnema MS (2006) Assessment of a construction-related eelgrass restoration in New Jersey. *Seagrass restoration: success, failure, and the cost of both*, eds Treat SF & Lewis RR (Lewis Environmental Services, Inc., Valrico, USA, Mote Marine Laboratory, Sarasota, March 11-12, 2003), pp 79-90.
28. Bos AR & van Katwijk MM (2005) *Herintroductie van Groot zeegras (Zostera marina) in de westelijke Waddenzee (2002-2005)* (Dep. of Environmental Science, Radboud University, Nijmegen, The Netherlands) pp 1-67.
29. Bos AR & van Katwijk MM (2007) Planting density, hydrodynamic exposure and mussel beds affect survival of transplanted intertidal eelgrass. *Marine Ecology-Progress Series* 336:121-129.
30. Burdett A, Poynor R, Linkogle J, & Schield S (2002) Joan M. Durante Park coastal restoration. *Proceedings of the 29th Annual Conference on Wetlands Restoration and Creation.* , ed Cannizzaro PJ (Hillsborough Community College, Tampa, Florida, USA), pp 28-32.
31. Busch KE & Golden RR (2009) *Large-scale restoration of eelgrass (Zostera marina) in the Patuxent and Potomac rivers, Maryland. Final report to National Oceanic and Atmospheric Administration* (Maryland Department of Natural Resources, Annapolis, Maryland, USA).
32. Busch KE*, et al.* (2010) Large-Scale *Zostera marina* (eelgrass) restoration in Chesapeake Bay, Maryland, USA. Part I: A comparison of techniques and associated costs. *Restoration Ecology* 18(4):490-500.
33. Cambridge ML & Kendrick GA (2009) Contrasting responses of seagrass transplants

(*Posidonia australis*) to nitrogen, phosphorus and iron addition in an estuary and a coastal embayment. *Journal of Experimental Marine Biology and Ecology* 371(1):34-41.

34. Campbell ML & Paling EI (2003) Evaluating vegetative transplant success in *Posidonia australis*: a field trial with habitat enhancement. *Marine Pollution Bulletin* 46(7):828-834.

35. Candela N (2008) Transplantation de pharnérogames marines dans les lagunes cotieres du Languedoc: Roussillon: Evaluation des résultats par l'études des interactions plantes/bactéries dans la rhizosphere. in *Mémoire de Master* (Université des Sciences et Techniques, Languedoc, France), pp 1-32.

36. Carangelo PD, Oppenheimer CH, & Picarazzi PE (1980) Biological application for the stabilization of dredged materials, Corpus Christi, Texas: submergent plantings. *Proceedings of the sixth annual conference on the restoration and creation of wetlands, 19 May 1979*, ed Cole DPTampa, Florida), pp 243-262.

37. Carannante F*, et al.* (2007) Sopravvivenza di talee di *Posidonia oceanica* trapiantate nella prateria di S. Marinella: risultati al secondo anno di monitoraggio. ed Pelosi G (Renato Casagrandi & Paco Melià, Ancona, Italy), pp 74-74.

38. Charbonnel E, Molenaar H, & Gravez V (1995) *Réimplantation de la phanérogame marine Posidonia oceanica dans le golfe de Marseille (Bouches du Rhône). Rapport final 1991-1995* (GIS Posidonie) pp 1-93.

39. Christensen PB, Sortkjaer O, & McGlathery KJ (1995) *Transplantation of eelgrass* (National Environmental Research Institute, Silkeborg) pp 1-15.

40. Churchill AC (1983) Field studies on seed germination and seedling development in *Zostera marina* L. *Aquatic Botany* 16:21-29.

41. Clark PA (1989) Seagrass restoration: a non-destructive approach. *Proceedings of the*

*16th Annual Conference on Wetlands Restoration and Creation.* , ed Webb FJ (Hillsborough Community College, Tampa, Florida, USA), pp 57-70.

42. Cottam C (1938) Status of eelgrass (*Zostera marina*) on the North Atlantic coast, February 1938. in *Wildlife Research and Management Leaflet BS-110* (United States Department of Agriculture, Bureau of Biological Survey, Washington), pp 1-6.

43. Cunha AH*, et al.* (2014) Biomares a LIFE project to restore and manage the biodiversity of Prof. Luiz Saldanha Marine Park. *Journal of Coastal Conservation* 18:643-655.

44. Curiel D, Scarton F, Rismondo A, & Marzocchi M (2005) Pilot transplanting project of *Cymodocea nodosa* and *Zostera marina* in the lagoon of Venice: results and perspectives. *Bollettino del Museo Civico di Storia Naturale di Venezia* 56:25-40.

45. Davis RC, Reel JT, Short FT, & Montoya D (2006) Costs and success of large-scale eegrass (*Zostera marina* L.) plantings in New England (New Hampshire and Maine). *Seagrass restoration: success, failure, and the cost of both*, eds Treat SF & Lewis RR (Lewis Environmental Services, Inc., Valrico, USA, Mote Marine Laboratory, Sarasota, March 11-12, 2003), pp 103-114.

46. Davis RC & Short FT (1997) Restoring eelgrass, *Zostera marina* L., habitat using a new transplanting technique: The horizontal rhizome method. *Aquatic Botany* 59:1-15.

47. Dennison WC & Alberte RS (1986) Photoadaptation and growth of *Zostera marina* L. (eelgrass) transplants along a depth gradient. *Journal of Experimental Marine Biology and Ecology* 98:265-282.

48. Derrenbacker J & Lewis RR (1982) Seagrass habitat restoration, Lake Surprise, Florida Keys. *Proceedings of the ninth annual conference on wetlands restoration and creation, May 17-18*, ed Webb FJTampa, USA), pp 132-154.

49. Durako MJ, Shup JJ, Andress CJ, & Tomasko DA (1993) Restoring seagrass beds: new

approaches with *Ruppia maritima* L. (Widgeon-grass). *Proceedings of the 20th Annual Conference on Wetlands Restoration and Creation.* , ed Webb FJ (Hillsborough Community College, Tampa, Florida, USA), pp 88-101.

50. Durako MJ, Shup JJ, Delon MF, & Daeschner SW (1995) A bioassay approach to seagrsas restoration. *Proceedings of the 22nd Annual Conference on Wetlands Restoration and Creation.* , eds Webb FJ & Cannizzaro PJ (Hillsborough Community College, Tampa, Florida, USA), pp 44-55.

51. Ehringer JN (2000) New and innovative techniques for seagrass restoration. *Proceedings of the 26th Annual Conference on Wetlands Restoration and Creation.* , ed Cannizzaro PJ (Hillsborough Community College, Tampa, Florida, USA), pp 18-26.

52. Ewanchuk PJ & Williams SL (1996) Survival and re-establishment of vegetative fragments of eelgrass (*Zostera marina*). *Canadian Journal of Botany* 74:1584-1590.

53. Fishman JR, Orth RJ, Marion S, & Bieri J (2004) A comparative test of mechanized and manual transplanting of eelgrass, *Zostera marina*, in Chesapeake Bay. *Restoration Ecology* 12(2):214-219.

54. Fonseca MS, Kenworthy WJ, Colby DR, Rittmaster KA, & Thayer GW (1990) Comparisons of fauna among natural and transplanted eelgrass *Zostera marina* meadows: Criteria for mitigation. *Marine Ecology-Progress Series* 65:251-264.

55. Fonseca MS, Kenworthy WJ, & Courtney FC (1996) Development of planted seagrass beds in Tampa Bay, Florida, USA: I. Plant components. *Marine Ecology-Progress Series* 132:127-139.

56. Fonseca MS, Kenworthy WJ, Homziak J, & Thayer GW (1980) Transplanting of eelgrass and shoalgrass as a potential means of ecomically mitigating a recent loss of habitat. *Proceedings of the sixth annual conference on the restoration and creation of wetlands,*

*May 19, 1979, Hillborough Community College*, ed Cole DPTampa, Florida, USA), pp 279-326.

57. Fonseca MS, Kenworthy WJ, & Thayer GW (1987) *Transplanting of the seagrasses Halodule wrightii, Syringodium filiforme, and Thalassia testudinum for sediment stabilization and habitat development in the southeast region of the United States* (Southeast FIsheries Center, Beaufort Laboratory, Beaufort, NC, USA) pp 1-59.

58. Fonseca MS, Kenworthy WJ, Thayer GW, Heller DY, & Cheap KM (1985) *Transplanting of the seagrasses Zostera marina and Halodule wrightii for sediment stabilization and habitat development on the east coast of the United States* (Southeast Fisheries Center, Beaufort Laboratory, Beaufort, NC, USA) pp 1-64.

59. Fonseca MS, Kenworthy WT, Courtney FX, & Hall MO (1994) Seagrass planting in the southeastern United States: Methods for accelerating habitat development. *Restoration Ecology* 2:198-212.

60. Fonseca MS, Meyer DL, & Hall MO (1996) Development of planted seagrass beds in Tampa Bay, Florida, USA: II. Faunal components. *Marine Ecology-Progress Series* 132:141-156.

61. Fukuda T, Kastutani K, & Terashima S (1984) Development of the techniques for marine macrophyte (*Zostera marina*) bed creation II. The effect of seeding and creation of sand bed. (Okayama Prefectural Fisheries Experimental Station, Kashino), pp 50-55.

62. Gayle PMH, Wilson-Kelly P, & Green S (2005) Transplantation of benthic species to mitigate impacts of coastal development in Jamaica. *Revista de Biologia Tropical* 53:105-115.

63. Genot I, Caye G, Meinesz A, & Orlandini M (1994) Role of chlorophyll and carbohydrate

contents in survival of *Posidonia oceanica* cuttings transplanted to different depths. *Marine Biology Berlin* 119(1):-29.

64. Giesen WBJT*, et al.* (2012) *Eindrapport van de Fasen 6-8: Monitoring van Zeegrasmitigaties uitgevoerd in 2007, 2008 & 2010, monitoring gedurende 2010-2011. Proeven met verplaatsen van Klein zeegras Zostera noltii in de Oosterschelde: mitigatiemaatregel bij toekomstige dijkwerkzaamheden. ZLD-6606A* (Radboud Universiteit, Nijmegen, The Netherlands) pp -.

65. Giesen WBJT, Giesen PT, Govers LL, Suykerbuyk W, & van Katwijk MM (2010) *Zeegrasmitigaties Oosterschelde. Proeven met verplaatsen van klein zeegras Zostera noltii in de Oosterschelde: mitigatiemaatregel bij toekomstige dijkwerkzaamheden. ZLD-6606, Eindrapportage fasen 3-5* (Radboud Universiteit, Nijmegen, The Netherlands) pp -.

66. Giesen WBJT, Giesen PT, van der Heide T, Suykerbuyk W, & van Katwijk MM (2008) *Zeegrasmitigaties Oosterschelde. Proeven met verplaatsen van klein zeegras Zostera noltii in de Oosterschelde: mitigatiemaatregel bij toekomstige dijkwerkzaamheden. Tussenrapportage fase 3: monitoring van zeegrasplots aangelegd in 2007* (ZLD-6606, Radboud Universiteit, Nijmegen, The Netherlands) pp 1-63.

67. Goforth HW & Peeling TJ (1980) Intertidal and subtidal eelgrass (*Zostera marina* L.) transplant studies in San Diego Bay, California. *Proceedings of the sixth annual conference on wetlands restoration and creation, May 19, 1979, Hillsborough Community College*, ed Cole DPTampa, Florida, USA), pp 1-25.

68. Hammerstrom K, Sheridan P, & McMahan G (1998) Potential for seagrass restoration in Galveston Bay, Texas. *Texas Journal of Science* 50(1):35-50.

69. Harmsen GW (1936) Systematische Beobachtungen der Nordwest-Europäischen

Seegrasformen. *Nederlands Kruidkundig Archief* 46:852-877.

70. Harrison PG (1990) Variations in success of eelgrass transplants over a five-years' period. *Environmental Conservation* 17:157-163.

71. Harwell MC & Orth RJ (1999) Eelgrass (*Zostera marina* L.) seed protection for field experiments and implications for large-scale restoration. *Aquatic Botany* 64(1):51-61.

72. Harwell MC & Rhode JM (2007) Effects of edge/interior and patch structure on reproduction in *Zostera marina* L. in Chesapeake Bay, USA. *Aquatic Botany* 87(2):147-154.

73. Heidelbaugh WS*, et al.* (1999) Reciprocal transplanting of the threatened seagrass *Halophila johnsonii* (Johnson's Seagrass) in the Indian River Lagoon, Florida. *Seagrases. Monitoring, ecology, physiology, and management*, ed Bortone SA (CRC Press), pp 177-193.

74. Hermus DCR (1995) *Herintroduktie van zeegras in de Waddenzee. Het verloop van de beplantingen in 1992-1994 & zaadexperimenten* (Department of Aquatic Ecology and Environmental Biology, University of Nijmegen) pp 1-94.

75. Homziak J, Fonseca MS, & Kenworthy WJ (1982) Macrobenthic community structure in a transplanted eelgrass (*Zostera marina*) meadow. *Marine Ecology-Progress Series* 9:211-221.

76. Horn LE, Paling EI, & van Keulen M (2009) Photosynthetic recovery of transplanted *Posidonia sinuosa*, Western Australia. *Aquatic Botany* 90(2):149-156.

77. Hovey RK & Cambridge ML (2010) *Seagrass Monitoring in Owen Anchorage Mooring Scars. Report to Oceanica Consulting* (Perth, West Australia) pp 1-17.

78. Irving AD*, et al.* (2010) Testing alternate ecological approaches to seagrass rehabilitation: links to life-history traits. *Journal of Applied Ecology* 47(5):1119-1127.

79. Kagawa Prefecture (2007) *Guidelines for eelgrass restoraiton in Kagawa Prefecture*.

80. Kasagai Y, Hisamoto T, Nakayama K, & Matsumoto H (2003) Tidal flat restoration projects at Onomichi-Itozaki Port, Hiroshima, Japan. (In Japanese, with English abstract). *Annual Journal of Civil Engineering in the Ocean* 19:107-112.

81. Kelly JA, Fuss CM, & Hall JR (1971) Transplanting and Survival of Turtle Grass, Thalassia-Testudinum, in Boca Ciega Bay, Florida. *Fishery Bulletin of the National Oceanic and Atmospheric Administration* 69(2):273-&.

82. Kennedy EA, Fucik KW, & Mitchell DC (1986) Identification of sites and application of a mitigation program along the Texas coast. *Proceedings of the 13th Annual Conference on Wetlands Restoration and Creation.* , ed Webb FJ (Hillsborough Community College, Tampa, Florida, USA), pp 106-117.

83. Kenworthy WJ & Fonseca MS (1992) The use of fertilizer to enhance growth of transplanted seagrasses *Zostera marina* L. and *Halodule wrightii* Aschers. *Journal of Experimental Marine Biology and Ecology* 163:141-161.

84. Kenworthy WJ, Fonseca MS, Homziak J, & Thayer GW (1980) Development of a transplanted seagrass (*Zostera marina L.)* meadow in Back Sound, Carteret County, North Carolina. *Proceedings of the seventh annual conference on the restoration and creation of wetlands, May 16-17, 1980, Contribution number 80-55B*, ed Cole DP), pp 174-194.

85. Kirkman H (1998) Pilot experiments on planting seedlings and small seagrass propagules in Western Australia. *Marine Pollution Bulletin* 37(8-12):460-467.

86. Kiswara W (2010) Transplantasi lamun *Enhalus Acoroides* I: Pengaruh kerapatan tunas terhadap lulus hidup bibit di pulau Bidadari, Teluk Jakarta. *Dinamika ekosystem perairan Kepalauan Seribu, Teluk Jakarta*, eds Nuchsin R, Sulistijo, Pramadji, Tjutju S, &

Muswerry M (Pusat Penelitian Oseanografi, LIPI, Jakarta, Indonesia), pp 192-200.

87. Kiswara W, Bouma TJ, Huiskes AHL, & Herman PMJ (2010) Survival and development transplant single shoots of *Enhalus acoroides* L.f. Royle in different morphological types at Banten Bay, Indonesia. *World Seagrass Conference*, pp 77-77.

88. Kiswara W & Ulumuddin YI (2010) Transplantasi lamun *Enhalus acoroides* II: pengaruh kompos terhadap pertumbuhan bibit di pulau Pari, Teluk Jakarta. *Dinamika ekosistem perairan Kepulauan Seribu, Teluk Jakarta*, eds Nuchsin R, Sulistijo, Pramadji, Tjutju S, & Muswerry M (Pusat Penelitian Oseanografi, LIPI, Jakarta, Indonesia), pp 201-215.

89. Koshikawa Y*, et al.* (2006) A new technology of seeling production ofr speedy restoration of eelgrass (*Zostera marina*) bed. (In Japanese, with English abstract). *Annual Journal of Civil Engineering in the Ocean* 22:625-630.

90. Lamson AL (1949) *Eelgrass restoration program. Annual report January 1, 1947 - December 31, 1947* (Connecticut State Board of Fisheries and Game.) p 16.

91. Lanuru M (2011) Bottom sediment characteristics affecting the success of seagrass (*Enhalus acoroides*) transplantation in the westcoast of South Sulawesi (Indonesia). *2011 3rd International Conference on Chemical, Biological and Environmental Engineering IPCBEE vol. 20*, (IACSIT Press, Singapore), pp 97-102.

92. Lee KS (2007) *Seagrass habitat restoration for improvements of coastal ecosystem and production* (Report Ministry of Land Transport and Maritime Affairs of Korea) pp 1-113.

93. Lee KS (2010) *Seagrass habitat restoration in the Taehwa river estuary and development of an effective management technique* (Report Ministry of Land Transport and Maritime Affairs of Korea) pp 1-60.

94. Lee KS & Park JI (2008) An effective transplanting technique using shells for restoration of *Zostera marina* habitats. *Marine Pollution Bulletin* 56(5):1015-1021.

95. Lepoint G*, et al.* (2004) Nitrogen dynamics in *Posidonia oceanica* cuttings: implications for transplantation experiments. *Marine Pollution Bulletin* 48(5-6):465-470.

96. Leschen AS, Ford KH, & Evans NT (2010) Successful eelgrass (*Zostera marina*) restoration in a formerly eutrophic estuary (Boston Harbor) supports the use of a multifaceted watershed approach to mitigating eelgrass loss. *Estuaries and Coasts* 33(6):1340-1354.

97. Leschen AS, Kessler RK, & Estrella BT (2009) *Eelgrass restoration used as construction impact mitigation in Boston Harbor, Massachusetts.* (Massachusetts Division of Marine Fisheries Technical Report TR-37, Gloucester, Massachusetts, USA).

98. Lewis RR (1987) The restoration and creation of seagrass meadows in the southeastern United States. *Proceedings of the symposium on subtopical seagrasses of the southeastern United States.*, eds Durako MJ, Phillips RC, & Lewis RR (Fla. Dept. of Natural Resources Mar. Res.Pub. no 42., St Petersburg, Florida, USA), pp 153-173.

99. Lewis RR, Kruer CR, Treat SF, & S.M. M (1994) *Wetland mitigation evaluation report Florida Keys bridge replacement.* (State of Florida, Dept Transportation, Environmental Management Office, Tallahassee, Florida, USA).

100. Lewis RR, Marshall MJ, Bloom SA, Hodgson AB, & Flynn LF (2006) Evaluation of the success of seagrass mitigation at Port Manatee, Tampa Bay, Florida. *Seagrass restoration: success, failure and the cost of both. Proceedings of the conference. Mote Marine Laboratory, March 2003*, eds Treat SF & Lewis RR (Lewis Environmental Services., Tampa, Florida, USA), pp 19-40.

101. Li WT, Kim JH, Park JI, & Lee KS (2010) Assessing establishment success of *Zostera marina* transplants through measurements of shoot morphology and growth. *Estuarine Coastal And Shelf Science* 88(3):377-384.

102. Liu YG & Wang GH (2006) Application on transplanting eelgrass (*Zostera marina* L.) into sea cucumber ponds. (In Chinese). *Shandong Fishery* 23:12.

103. Lynch JJ & Cottam C (1937) *Status of eelgrass (Zostera marina) on the north Atlantic coast, January 1937. Wildlife Research and Management LEaflet BS-94* (United States Department of Agriculture, Bureau of Biological Survey) p 15.

104. Marion SR & Orth RJ (2010) Innovative techniques for large-scale seagrass restoration using *Zostera marina* (eelgrass) seeds. *Restoration Ecology* 18(4):514-526.

105. Marion SR & Orth RJ (2010) Factors influencing seedling establishment rates in *Zostera marina* and their implications for seagrass restoration. *Restoration Ecology* 18(4):549-559.

106. McGlathery KJ*, et al.* (2012) Recovery trajectories during state change from bare sediment to eelgrass dominance. *Marine Ecology Progress Series* 448:209-221.

107. McLaughlin PA, Treat SF, Thorhaugh A, & Lemaitre R (1983) A restored seagrass (*Thalassia*) bed and its animal community. *Environmental Conservation* 10:247-254.

108. McNeese PL*, et al.* (2006) Topographic restoration of boat grounding damage at the Lignumvitae Submerged Land Management Area. *Seagrass restoration: success, failure, and the cost of both*, eds Treat SF & Lewis RR (Lewis Environmental Services, Inc., Valrico, USA, Mote Marine Laboratory, Sarasota, March 11-12, 2003), pp 131-146.

109. Meehan AJ & West RJ (2002) Experimental transplanting of *Posidonia australis* seagrass in Port Hacking, Australia, to assess the feasibility of restoration. *Marine Pollution Bulletin* 44(1):25-31.

110. Meinesz A (1977) Note préliminaire concernant le repiquage de végétaux marins, en particulier de l'algue Caulerpa prolifera.), pp 169-170.

111. Meinesz A (1978) Etude expérimentale de bouturage de certains végétaux sous marins

dans les ports et les plages artificielles.), pp 9-14.

112. Meinesz A (1993) *Transplantations de Posidonia oceanica devant le port de Vallauris - Golfe Juan. Report Laboratoire Environnement Marin littoral,* (Université de Nice Sophia Antipolis, Nice, France) pp 1-48.

113. Meinesz A, Caye G, Loques F, & Molenaar H (1993) Polymorphism and development of *Posidonia oceanica* transplanted from different parts of the Mediterranean into the national park of Port-Cros. *Botanica Marina* 36(3):209-216.

114. Meinesz A, Molenaar H, Bellone E, & Loquès F (1992) Vegetative reproduction in *Posidonia oceanica*: 1. Effects of rhizome length and transplantation season in orthotropic shoots. *Marine Ecology-Pubblicazioni Della Stazione Zoologica di Napoli I* 13:163-174.

115. Merkel & Associates I (2009) Eelgrass & Cordgrass. *Batiquitos Lagoon long-term biological monitoring program. Final Report. M&A Doc.No. 96-057-01-F*, ed Merkel & Associates ISan Diego, California, USA), pp 1-26.

116. Merkel KW (1990) Eelgrass transplanting in South San Diego Bay, California. *Proceedings of the California Eelgrass Symposium, May 27 and 28, 1988*, eds Merkel KW, Hoffman RS, & J.L. SChula Vista, California), pp 28-42.

117. Merkel KW (1990) Growth & survival of transplanted eelgrass: the importance of planting unit size and spacing. *Proceedings of the California Eelgrass Symposium, May 27 and 28, 1988*, eds Merkel KW, Hoffman RS, & J.L. SChula Vista, California), pp 70-78.

118. Milano GR & Deis DR (2006) Biscayne Bay seagrasses and recent restoration efforts. *Seagrass restoration: success, failure, and the cost of both*, eds Treat SF & Lewis RR (Lewis Environmental Services, Inc., Valrico, USA, Mote Marine Laboratory, Sarasota, March 11-12, 2003), pp 115-130.

119. Ministry of the Environment J (2004) Considerations regarding the restoration of seagrass beds. (In Japanese). (Tokyo), pp 1-100.

120. Molenaar H (1992) *Etude de la transplantation de boutures de Posidonia oceanica (L.)Delile, phanérogames marines. Modélisation de l'architecture et du mode de croissance.* (Thèse doctorat (PHD) Université de Nice Sophia Antipolis, Nice, France ) pp 1-221.

121. Molenaar H, Caye G, Loquès F, & Meinesz A (1989) *Tranplantation de Posidonia oceanica réalisées à Cannes en Juin 1989. Report Lab Environnement marin littoral* (Université Nice Sophia Antipolis, Nice, France) pp 1-23.

122. Molenaar H & Meinesz A (1991) *Transplantation de la phanérogame marine Posidonia oceanica à Cannes et analyse architecturale de rhizomes plagiotropes. Report Laboratoire Environnement Marin littoral,* (Université de Nice Sophia Antipolis, Nice, France) pp 1-30.

123. Molenaar H & Meinesz A (1992) Vegetative reproduction in *Posidonia oceanica* 2. Effects of depth changes on transplanted orthotropic shoots. *Marine Ecology-Pubblicazioni Della Stazione Zoologica di Napoli I* 13(2):175-185.

124. Molenaar H & Meinesz A (1992) *1- Transplantations de Posidonia oceanica à Nice. Report Laboratoire Environnement Marin littoral* (Université de Nice Sophia Antipolis, Nice, France) pp 1-26.

125. Molenaar H & Meinesz A (1995) Vegetative reproduction in *Posidonia oceanica*: survival and development of transplanted cuttings according to different spacings, arrangements and substrates. *Botanica Marina* 38:313-322.

126. Montin GJ & Dennis RF (2006) A shallow water technique for the successful relocation and/or transplantation of large areas of shoalgrass (*Halodule wrightii*). *Seagrass*

*restoration: success, failure, and the cost of both*, eds Treat SF & Lewis RR (Lewis Environmental Services, Inc., Valrico, USA, Mote Marine Laboratory, Sarasota, March 11-12, 2003), pp 41-48.

127. Moore KA, Neckles HA, & Orth RJ (1996) *Zostera marina* (eelgrass) growth and survival along a gradient of nutrients and turbidity in the lower Chesapeake Bay. *Marine Ecology-Progress Series* 142(1-3):247-259.

128. Morita K, Hamabata M, Masuhara H, Fukase K, & Kawasaki Y (2002) *Zostera* (eelgrass) bed restoration in Japan. *Fisheries Science* 68:1771-1774.

129. Mueller E & Sukup M (1988) Experimental plots of *Halodule wrightii* in a closed, aerated canal system (Little Torch Key, Florida). *Proceedings of the 15th Annual Conference on Wetlands Restoration and Creation.* , ed Webb FJ (Hillsborough Community College, Tampa, Florida, USA), pp 208-220.

130. Nieri M, Meinesz A, Molenaar H, & Sloeck O (1991) *Réimplantation de la phanérogame Posidonia oceanica dans le golfe de Marseille (Bouches-du- Rhône). Transplantation et état initial* (Report GIS Posidonie) pp 1-35.

131. Noé V (2007) Restauration des milieux lagunaires vis à vis de l'eutrophisation en languedoc-Roussillon. in *Mémoire de Master* (Université de la Méditerranée, France), pp 1-51.

132. Noten TMPA (1983) Detached shoots of *Zostera noltii* Hornem. as a means of dispersal: a transplantation experiment. Nijmegen, 18-23 September 1983), pp -.

133. Omoto S, Torii M, Miura S, Manabe K, & Nishimura K (2005) Growth of an artificial eelgrass bed on the coast of Ninase-cho, Okayama prefecture. (In Japanese with English abstract). *Fisheries Engineering* 42:75-78.

134. Orth RJ*, et al.* eds (2006) *A review of techniques using adult plants and seeds to*

*transplant eelgrass (Zostera marina L.) in Chesapeake Bay and the Virginia Coastal Bays*Sarasota, Florida), p 175.

135. Orth RJ, Fishman JR, Harwell MC, & Marion SR (2003) Seed-density effects on germination and initial seedling establishment in eelgrass Zostera marina in the Chesapeake Bay region. *Marine Ecology-Progress Series* 250:71-79.

136. Orth RJ, Harwell MC, & Fishman JR (1999) A rapid and simple method for transplanting eelgrass using single, unanchored shoots. *Aquatic Botany* 64(1):77-85.

137. Orth RJ, Luckenbach ML, Marion SR, Moore KA, & Wilcox DJ (2006) Seagrass recovery in the Delmarva Coastal Bays, USA. *Aquatic Botany* 84(1):26-36.

138. Orth RJ, Marion SR, Granger S, & Traber M (2009) Evaluation of a mechanical seed planter for transplanting *Zostera marina* (eelgrass) seeds. *Aquatic Botany* 90(2):204-208.

139. Orth RJ, Marion SR, Moore KA, & Wilcox DJ (2010) Eelgrass (*Zostera marina* L.) in the Chesapeake Bay region of Mid-Atlantic coast of the USA: Challenges in conservation and restoration. *Estuaries and Coasts* 33(1):139-150.

140. Orth RJ, Moore KA, Marion SR, & Anderson B (2007) *Eelgrass restoration in the Piankatank River, Chesapeake Bay.* (Final Report National Oceanic and Atmospheric Administration NA03NMF4570462).

141. Orth RJ, Moore KA, Marion SR, Wilcox DJ, & Parrish DB (2012) Seed addition facilitates eelgrass recovery in a coastal bay system. *Marine Ecology Progress Series* 448:177-195.

142. Paling EI, van Keulen M, & Tunbridge DJ (2007) Seagrass transplanting in Cockburn Sound, Western Australia: A comparison of manual transplantation methodology using *Posidonia sinuosa* Cambridge et Kuo. *Restoration Ecology* 15(2):240-249.

143. Paling EI, van Keulen M, Wheeler K, Phillips J, & Dyhrberg R (2001) Mechanical seagrass

transplantation in Western Australia. *Ecological Engineering* 16(3):331-339.

144. Paling EI, van Keulen M, Wheeler K, & Walker C (2000) Effects of depth on manual transplantation of the seagrass *Amphibolis griffithii* (J. M. Black) den Hartog on Success Bank, Western Australia. *Pacific Conservation Biology* 5(4):314-320.

145. Paling EI, van Keulen M, & Wheeler KD (1998) *Seagrass rehabilitation in Owen Anchorage, Western Australia* (Report no. MAFRA 98/4, Murdoch University, Murdoch) pp 1-32.

146. Paling EI, van Keulen M, Wheeler KD, Phillips J, & Dyhrberg R (2003) Influence of spacing on mechanically transplanted seagrass survival in a high wave energy regime. *Restoration Ecology* 11(1):56-61.

147. Paling EI*, et al.* (2001) Improving mechanical seagrass transplantation. *Ecological Engineering* 18(1):107-113.

148. Park JI & Lee KS (2007) Site-specific success of three transplanting methods and the effect of planting time on the establishment of *Zostera marina* transplants. *Marine Pollution Bulletin* 54(8):1238-1248.

149. Park JI & Lee KS (2010) Development of transplantation method for the restoration of surfgrass, *Phyllospadix japonicus*, in an exposed rocky shore using an artificial underwater structure. *Ecological Engineering* 36(4):450-456.

150. Phillips RC (1974) Transplantation of seagrasses, with special emphasis on eelgrass, *Zostera marina* L. *Aquaculture* 4:161-176.

151. Phillips RC (1980) Transplanting methods. eds Phillips RC & McRoy CP (Garland Press, New York), pp 41-56.

152. Phillips RC (1980) Responses of transplanted and indigenous *Thalassia testudinum* Banks Ex Konig and *Halodule wrightii* Aschers to sediment loading and cold stress.

*Contributions In Marine Science* 23(AUG):79-87.

153. Phillips RC (1996) Ecology of eelgrass (*Zostera marina* L.) transplants in Izembek Lagoon, Alaska. eds Kuo J, Phillips RC, Walker DI, & Kirkman H (25-29 January 1996, Rottnest Island, Western Australia), pp 333-338.

154. Phillips RC & Lewis RL, III (1983) Influence of environmental gradients on variations in leaf width and transplant success in North American seagrasses. *Marine Technology Society Journal* 17(2):59-68.

155. Phillips RC, Vincent MK, & Huffman RT (1978) Habitat development field investigations, Port St. Joe seagrass demonstration site Port St. Joe, Florida.

156. Piazzi L, Balestri E, & Magri M (1999) A preliminary study on the effects of some plant growth regulators on *Posidonia oceanica* (L.) Delile transplants. *Biologia Marina Mediterranea* 6:508-509.

157. Piazzi L, Balestri E, Magri M, & Cinelli F (1998) Experimental transplanting of *Posidonia oceanica* (L.) Delile into a disturbed habitat in the Mediterranean Sea. *Botanica Marina* 41(6):593-601.

158. Pickerell CH, Schott S, & Wyllie-Echeverria S (2005) Buoy-deployed seeding: Demonstration of a new eelgrass (Zostera marina L.) planting method. *Ecological Engineering* 25(2):127-136.

159. Pranovi F, Curiel D, Rismondo A, Marzocchi M, & Scattolin M (2000) Variations of the macrobenthic community in a seagrass transplanted area of the Lagoon of Venice. *Scientia Marina* 64(3):303-310.

160. R. N (1990) Morro Bay eelgrass transplant. *Proceedings of the California Eelgrass Symposium, May 27 and 28, 1988*, eds Merkel KW, Hoffman RS, & J.L. SChula Vista, California), pp 43-45.

161. Ranwell DS, Wyer DW, Boorman LA, Pizzey JM, & Waters RJ (1974) *Zostera* transplants in Norfolk and Suffolk, Great Britain. *Aquaculture* 4:185-198.

162. Ren GZ, Zhang QX, Wang JC, & Wang DJ (1991) Transplanting eelgrass in shrimp ponds to increase products of *Penaeus chinensis* O'sbeck. (In Chinese). *Mar. Sci.* 1:52-27.

163. Rodriguez-Salinas P, Riosmena-Rodriguez R, Hinojosa-Arango G, & Muniz-Salazar R (2010) Restoration experiment of *Zostera marina* L. in a subtropical coastal lagoon. *Ecological Engineering* 36(1):12-18.

164. Sanchez-Lizaso JL, Fernandez-Torquemada Y, & Gonzalez-Correa JM (2009) Evaluation of the viability of *Posidonia oceanica* transplants associated with a marina expansion. *Botanica Marina* 52(5):471-476.

165. Shafer DJ (2008) *GigaUnit transplant system: a new mechanical tool for transplanting submerged aquatic vegetation* (Technical note ERDC/TN SAV-08-2).

166. Shafer DJ & Bergstrom P (2008) Large-scale submerged aquatic vegetation restoration in Chesapeake Bay. (Washington), pp 1-79.

167. Sheridan P (2004) Comparison of restored and natural seagrass beds near Corpus Christi, Texas. *Estuaries* 27(5):781-792.

168. Sheridan P, Henderson C, & McMahan G (2003) Fauna of natural seagrass and transplanted *Halodule wrightii* (shoalgrass) beds in Galveston Bay, Texas. *Restoration Ecology* 11(2):139-154.

169. Sheridan P, McMahan G, Hammerstrom K, & Pulich W, Jr. (1998) Factors affecting restoration of *Halodule wrightii* to Galveston Bay, Texas. *Restoration Ecology* 6(2):144-158.

170. Shimokawa C (1991) Test of *Zostera* bed creation in Hiuchi-nada waters. *Journal of Seaweed Research Group of Nansei Sea Zone* 9:25-34.

171. Short FT, Davis RC, Kopp BS, Gaeckle JL, & Burdick DB (2006) Using TERFS and site selection for improved eelgrass restoration success. *Seagrass restoration: success, failure, and the cost of both*, eds Treat SF & Lewis RR (Lewis Environmental Services, Inc., Valrico, USA, Mote Marine Laboratory, Sarasota, March 11-12, 2003), pp 59-68.

172. Shu L, Chen P, Jia X, Li C, & Li X (2011) Seagrass transplantation in artificial fishing reefs and limited factor. *Journal of Fishery Sciences of China* 18:893-898.

173. Smith I, Fonseca MS, Rivera JA, & Rittmaster KA (1989) Habitat value of natural versus recently transplanted eelgrass, *Zostera marina*, for the bay scallop, *Argopecten irradians*. *Fishery Bulletin* 87:189-196.

174. Stutes JJ*, et al.* (2009) An exercise in eelgrass restoration in Bellingham Bay: a tale of two methods. *The annual Pacific Estuarine Research Society meeting, April 2-5, 2009*, Bellingham, Washington, USA), pp 1-x.

175. Suykerbuyk W*, et al.* (2012) Suppressing antagonistic bioengineering feedbacks doubles restoration success. *Ecological Applications* 22(4):1224-1231.

176. Takayama Y, Katakura N, Ueno S, & Yuasa S (2008) Field experiment of *Zostera japonica* transplanting using mattress method in Ago Bay. *Annual Journal of Coastal Engineering* 55:1266-1270.

177. Tamaki H, Tokuoka M, Nishijima W, Terawaki T, & Okada M (2002) Deterioration of eelgrass, *Zostera marina* L., meadows by water pollution in Seto Inland Sea, Japan. *Marine Pollution Bulletin* 44(11):1253-1258.

178. Tanner C*, et al.* (2010) Evaluating a large-scale eelgrass restoration project in the Chesapeake Bay. *Restoration Ecology* 18(4):538-548.

179. Tashibu H, Fukuoka K, Miyazawa T, & Tamori H (1986) Studies on the ecology of *Zostera* spp. and the environmental conditions and development of *Zostera* bed

creation method.), pp 93-102.

180. Terawaki T, Shimaya M, & Moriguchi A (2005) Excellent examples of eelgrass *Zostera marina* bed restoration continuing along the coast of Seto Inland Sea, Japan. (In Japanese, with English abstract). *Fisheries Engineering* 42:151-157.

181. Thom R, Southard J, Williams G, Blanton S, & Borde A (2000) *Eelgrass restoration at west eagle harbor phase 3: monitoring and evaluation*.

182. Thorhaug A (1974) Transplantation of the seagrass *Thalassia testudinum* Koenig. *Aquaculture* 4:177-183.

183. Thorhaug A (1980) Environmental-management of a highly impacted, urbanized tropical estuary - rehabilitation and restoration. *Helgolander Meeresuntersuchungen* 33(1-4):614-623.

184. Thorhaug A (1980) *Report on Matthew Strumor marine lake restoration test plots.* (Seagrass and marine macroalgae, Islamorada, Florida, USA).

185. Thorhaug A (1980) Growth of *Thalassia* restored by seedlings in a multiply-impacted estuary. *Proceedings of the sixth annual conference on wetlands restoration and creation, May 19 1979, Hillsborough Community College*, ed Cole DPTampa, Florida, USA), pp 264-278.

186. Thorhaug A (1985) Large-scale seagrass restoration in a damaged estuary. *Marine Pollution Bulletin* 16:55-62.

187. Thorhaug A (1987) Large-Scale Seagrass Restoration in A Damaged Estuary. *Marine Pollution Bulletin* 18(8):442-446.

188. Thorhaug A (1987) *Coastal rehabilitation through seagrass transplantation, Philippines* (FAO FAO-FI-TCP/PHI/4511, Rome, Italy) p 52.

189. Thorhaug A (1994) *Seagrass mitigation test plos and plans for the Laguna Madre,*

*Texas* (Report to the Fina Oil & Chemical Company, Houston, Texas, USA).

190. Thorhaug A (2001) Petroleum industry's use of seagrass restoration as a mitigation for construction and as a potential cleanup tool. *Proceedings International Oil spill Conference*, (APT/EPA/USCG), pp 386-391.

191. Thorhaug A & Cruz RT (1988) Seagrass restoration in the Pacific tropics. *Proc. of the 6th Int. Coral Reef Symp. Vol. 2*, ed Choat JHeaTownsville, Australia).

192. Thorhaug A & Hixon R (1975) Revegetation of *Thalassia testudinum* in a multiple-stresses estuary, North Biscayne Bay, Florida. in *Proc. Second Annual Conference on Restoration of Coastal Vegetation in Florida Hillsborough Community College*, ed Lewis RR (Tampa, FL, USA), pp 12-27.

193. Thorhaug A & McLaughlin PA (1980) Restoration of *Thalassia testudinum*: animal community in a maturing four-year-old site - preliminary results. *Proc. fifth Annual Conference on Restoration of Coastal Vegetation in Florida, May 13, 1978*, eds Cole DP & Lewis RR (Hillsborough Community College Press, Tampa, FL, USA), pp 149-161.

194. Thorhaug A, Miller B, Jupp B, & Booker F (1985) Effects of a variety of impacts on seagrass restoration in Jamaica. *Marine Pollution Bulletin* 16(9):355-360.

195. Thorhaugh A (1983) Habitat restoration after pipeline construction in a tropical estuary: seagrasses. *Marine Pollution Bulletin* 14:422-425.

196. Tokyo Metropolitan Government (2008) *Rapid report of projects (In Japanese, abstract only)* (Tokyo).

197. Tokyo Metropolitan Government (2009) *Rapid report of projects. (In Japanese, abstract only).* (Tokyo).

198. Tokyo Metropolitan Government TKl (1996) *Report of examinations of eelgrass transplantation in a bay (In Japanese)*.

199. Uhrin AV, Hall MO, Merello MF, & Fonseca MS (2009) Survival and expansion of mechanically transplanted seagrass sods. *Restoration Ecology* 17(3):359-368.

200. van Breedveld JF (1975) *Transplanting of seagrasses with emphasis on the importance of substrate*.

201. van Katwijk MM*, et al.* (2009) Guidelines for seagrass restoration: importance of habitat selection and donor population, spreading of risks, and ecosystem engineering effects. *Marine Pollution Bulletin* 58:179-188.

202. van Katwijk MM & Hermus DCR (2000) Effects of water dynamics on *Zostera marina*: transplantation experiments in the intertidal Dutch Wadden Sea. *Marine Ecology-Progress Series* 208:107-118.

203. van Katwijk MM & Schmitz GHW (1993) *Herintroduktie van Zeegras in de Waddenzee. Beplantingen 1991 en 1992* (Department of Aquatic Ecology and Environmental Biology, University of Nijmegen) pp 1-12.

204. van Keulen M, Paling EI, & Walker CJ (2003) Effect of planting unit size and sediment stabilization on seagrass transplants in Western Australia. *Restoration Ecology* 11(1):50-55.

205. van Pelt S, van Katwijk MM, & Dankers N (2003) *Herintroductie Zostera marina in de westelijke Waddenzee (2002-2006). Resultatenrapportage activiteiten 2002* (Report Dep. of Environmental Studies, University of Nijmegen) pp 1-65.

206. Vangeluwe D, Lepoint G, Bouquegneau JM, & Gobert S (2004) Effect of transplantation on *Posidonia oceanica* shoots. *Vie et Milieu-Life and Environment* 54(4):223-230.

207. Verduin JJ, Paling EI, Pedretti Y, Rivers L, & van Keulen M (submitted *Applied Ecology*) Successful seagrass restoration: evidence from a long-term large-scale study.

208. Verduin JJ, Paling E, van Keulen M, & Rivers L (2012) Recovery of donor meadows of

*Posidonia sinuosa* and *Posidonia australis* contributes to sustainable seagrass transplantation. *International Jounal of Ecology* 2012:1-5.

209. Wear RJ, Tanner JE, & Hoare SL (2010) Facilitating recruitment of *Amphibolis* as a novel approach to seagrass rehabilitation in hydrodynamically active waters. *Marine and Freshwater Research* 61(10):1123-1133.

210. West RJ, Jacobs NE, & Roberts DE (1990) Experimental transplantation of seagrasses in Botany Bay, Australia. *Marine Pollution Bulletin* 21:197-203.

211. Williams SL (2001) Reduced genetic diversity in eelgrass transplantations affects both population growth and individual fitness. *Ecological Applications* 11(5):1472-1488.

212. Yamaguchi Prefecture (2006) *Guidelines for eelgrass restoration in Yamaguchi Prefecture*.

213. Yamaki K, Shimbo Y, Tanaka M, Mitomi R, & Ogawa H (2006) Study on expansion of eelgrass bed and new colony formation by seedling transplant. *Annual Journal of Coastal Engineering* 53:1006-1010.

214. Yamamoto S, Nakase K, Yamamoto Y, Habara H, & Okada M (2004) Surviving and spreading of transplanted *Zostera marina* abed caused by physical environmental changes. (In Japanese). *Annual Journal of Coastal Engineering* 51:1041-1045.

215. Zimmerman RC, Reguzzoni JL, & Alberte RS (1995) Eelgrass (*Zostera marina* L.) transplants in San Francisco Bay: role of light availability on metabolism, growth and survival. *Aquatic Botany* 51:67-86.